NUTRITIONAL VALUE AND BENEFITS OF FOOD WASTE AS POTENTIAL FEED INGREDIENTS IN SWINE DIETS

A THESIS
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

CO-ADVISORS

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August 2019

Acknowledgements

First, I would like to express my sincere gratitude to my academic advisors, Drs. Gerald Shurson and Pedro Urriola. They have given me immense support and many learning opportunities throughout both my undergraduate and master's program. They have been critical in helping me to develop as a science researcher and I am grateful for the mentorship I have received throughout these years.

Secondly, I would also like to thank you both the advisors and graduate students in the Integrated Animal Systems Biology team for academic guidance and help in various projects. A special thank you to Dr. Milena Saqui-Salces for providing insights throughout different projects.

Dedication

I would like to dedicate this thesis to my parents Henry Fung and Cherry Chan along with my wife, Joanne Huang for their love and support.

Abstract

The increasing generation of food waste over the past decades has become a prominent threat to both the society and the environment in terms of food security, wasting limited natural resources and pollution. The objective of this thesis was to quantify the nutritional, economic, and environmental value of food waste derived at multiple sources as swine feed in order to divert these wasted materials into a reusable form to salvage the resources. Chapter 2 explored the different sources of food waste from the generation streams and determined that food waste generated at the upper stream of the food supply chain have greater values than the ones generated at the lower part of the chain. We then evaluated the feeding value of different upper stream food waste- *in-vivo* such as Fish Waste, Supermarket Waste and Fruit and Vegetable Waste in Chapter 3. The results concluded that supermarket waste has the greatest potential to be utilized as animal feed owing to its high amino acid and energy content. Finally, in Chapter 4 we explored the possible environmental benefits of these food waste sources in which supermarket waste appeared to be most environmentally advantageous when used to replace traditional ingredients such as corn and soybean meal. Overall, it appears that food waste, especially those generated upstream, has great value to be used as animal feed considering both nutritionally and environmentally. To conclude, the information discussed in the thesis can help establish the basic knowledge of how food waste can be utilized in farm animals feeding programs and hence, providing confidence to reducing the overall volume of wasted food in the society and increasing the sustainability of our food system.

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1. Introduction

The continuation of the global population increase and intensifying climate changes in the current Anthropocene requires dramatic improvement in the sustainability of our food system to achieve global food security when the world population reaches 9.6 billion by 2050 (Rockström et al., 2017). Perhaps one of the most significant steps that can be taken is to reduce the amount of wasted food. In 2011, approximately one-third of all the food generated for human consumption in the world was either lost or wasted, and is equivalent to a staggering 1.3 billion tons food waste materials (Gustavsson et al., 2011). Over the entire food chain, the generation of food losses occurs at multiple stages beginning at harvest, with subsequent losses occurring during transport, processing, product evaluation, packaging, distribution, and ultimately post-consumption (Parfitt et al., 2010). At the distribution stage, many major food waste sources such as restaurants, schools, institutions, grocery stores, and households are involved (Parfitt et al., 2010).

Food waste is typically defined as food losses that occur at the end of the food chain (retail and final consumption) and includes food that was intended for human consumption but was wasted due to retailer and consumer behavior (Parfitt et al., 2010). According to Bellemare et al. (2017), various organizations and agencies use different definitions to describe food waste, in which no standard definition has been adopted nor recognized by all government agencies. For example, the Food and Agriculture Organization of the United Nations (FAO) and U.S. Department of Agriculture's

Economic Research Services (ERS) defines food waste as materials that ends up in landfills as well as food waste recovered for other purposes (Bellemare et al., 2017). However, the U.S. Environmental Protection Agency (EPA) does not account for the proportion of food that is recovered throughout the food supply chain, but instead, accounts for only the proportion of food that is disposed in landfill from the retail and household stages of the food supply chain. Therefore, this definition of food waste neglects the food waste generated at the first stages of the food chain which include the grower and processing stages (Bellemare et al., 2017). However, it is worth noting that an estimated 95% of food waste generated at the industrial processing stages are generally recovered for other usages with majority of it being used as animal feed (ReFED, 2016a).. In contrast, less than 10% of food waste is recovered from consumer sources such as restaurants and stores (ReFED, 2016a). Consequently, it is important to recognize the differences in the definition of food waste adopted by different organizations and agencies when addressing the issue of food waste because the quantity and composition of waste streams can vary substantially between the definitions.

In the United States, approximately 40 % of the food produced is wasted annually, which represents approximately 60 million tons of organic material valued at $165 billion U.S. dollars per year, based on original retail sales price (ERS estimates; Gunders, 2012). In comparison, the value of global food waste in 2011 has been valued at $750 billion in U.S. dollars, or $470 per ton (FAO estimates; Gustavsson et al., 2011). Not only is there a significant annual financial loss to the global economy, but the huge quantities of food waste generated also causes multiple negative impacts on the global environment and societies.

2. Global Impact of Food Waste

The concerns caused by the enormous production of food waste can be classified into three major categories, which include direct and indirect economic, environmental, and social impacts. First, the economic concerns of food waste primarily relate to the complex process of collecting and disposing food waste, which cost local governments millions of dollars every year (Buzby and Hyman, 2012). These expenditures generally include collecting, transporting, storing, and processing, but the most significantly cost is landfilling. In 2010, the U.S. government spent approximately $1.3 billion in landfill costs for all of the food waste generated during that year (Buzby et al., 2014). From an overall perspective, the total cost of producing, processing, transporting, and disposing of unconsumed food products from farms to landfills is about $218 billion, and represents 1.3% of GDP in the United States annually (FAO estimates; ReFED, 2016). If these costs can be reduced, the cost savings could be used for other more valuable societal purposes such as investments in education and social welfare.

In addition to economic losses, food waste also causes significant negative environmental impacts such as unnecessary land use, increased greenhouse gas emissions, and excessive use of natural resources (Buzby and Hyman, 2012; Hall et al., 2009; Kowalska, 2017; Salemdeeb et al., 2017). For example, the average amount of food that was wasted in the U.S. in 2010 was estimated to be up to 195 kg per person, which represented 63 kg from retail food waste and 132 kg from consumer food waste (Buzby et al., 2014). According to the EPA, food waste accounts for 21.6% of the municipal solid waste in the United States, and compared with all other municipal waste materials (i.e.

metals, plastic, glass), food waste has the lowest rate of recovery, where about 95% of food waste was ultimately landfilled or combusted (USEPA, 2016a). Thus, the large amount of food waste that is being disposed in landfills annually, not only reduces the amount of land available for more useful purposes such as recreational facilities, “green space”, or food production, it also serves as a major contributor to the production of greenhouse gases (Buzby and Hyman, 2012; Hall et al., 2009). Parry et al. (2015) suggested that every ton of food waste produced results in 3.8 tons of greenhouse gases being emitted into the atmosphere. Researchers at the Waste and Resources Action Program in the United Kingdom concluded that “sending food waste to landfills is the worst possible option, creating an additional 536 kg of greenhouse gasses emission” (Parry et al., 2015). In the U.S., it has been estimated that organic matter in food waste accounts for 18% of the total methane gas produced from landfills each year (USEPA, 2016b). Methane gas is one of the most potent greenhouse gases, and traps 21 times more heat than carbon dioxide (Adhikari et al., 2006). Therefore, the high amount of methane produced from decomposing food waste enhances global warming and climate change (Hall et al., 2009). In addition, food waste disposal also causes excessive use of natural resources such as water, energy, and fuel (Kowalska, 2017). Food waste has been estimated to account for about 25% of the total fresh water use in agriculture in the United States, and approximately 300 million barrels of crude oil per year (Hall et al., 2009). Thus, the current vast amount of food wastage contributes to significant waste of finite natural resources such as fresh water and crude oil, which could be used for other productive purposes.

The enormous quantities of food waste also cause societal concerns related to global food security and long-term sustainability of food production that affect our future ability to feed an increasing global human population. The FAO has predicted that the world will require an increase of 70% in food production by 2050 in order to sustain the entire global human population (Gustavsson et al., 2011). The problem of world hunger had been dramatically decreasing over the past few decades due to the substantial improvement in productivity and efficiency of food production. Yet, one out of seven people in the world today still experience malnutrition resulting in none or limited access to adequate protein and energy foods (FAO, 2009). The uneven distribution of food production and availability related to world hunger can also lead to the instability of societies because productivity of a society depends on the availability of human capital and resources. The term "food riot" can be defined as "A violent, collective unrest leading to a loss of control, bodily harm or damage to property, essentially motivated by a lack of food availability, accessibility or affordability, as reported by the international media, and which may have other underlying causes of discontent" (Barbet-Gros and Cuesta, 2015). Once the food supply becomes unstable, societal problems such as violent crimes, political instability and protests can occur. For example, Madagascar and Haiti had major food price related protests in 2007 and 2008 when global food prices spiked (Bereuter and Glickman, 2017). Hence, the current situation of using limited natural resources to produce food that is ultimately wasted is an unreasonable practice that affects the stability of some societies. Searchinger et al. (2014) estimated that decreasing global food waste by 50% by 2050 would increase food security and decrease hunger by nearly 20%. Conversely, if strategies are not developed to overcome this food waste problem, it could result in global food waste production increasing to a much greater extent due to an increasing global population. In addition to world hunger, global urbanization, the expansion of the middle class in some countries will result in increasing wealth and buying power in the coming decades, and cause additional demands for the supply of food (Boland et al., 2013, Godfray et al.,2010). '

Searchinger et al. (2014) predicted that by 2030, the expanding global middle class will cause a drastic change in diet composition that involves the increase demand of animal-derived protein such as fish, meat and dairy products (Searchinger et al., 2014). Thus, the increase of animal protein demand will add a significant pressure in global food production due to the higher demand of resources needed to produce animal protein compared with the amount of resources to produce grains and other plant-based foods.

In summary, to reduce global economic, societal, and environmental concerns associated with the generation and disposal of food waste, alternative strategies for managing food waste must be developed to enhance global food security and sustainability (Morone et al., 2016). Several methods have been proposed to recycle food waste instead of directly disposing this potentially useful organic material (rich in nutrient content) in landfills, which include industrial use for biofuel production, composting, and processing into animal feed (Salemdeeb et al., 2016).

3. Current status and management methods for recycling food waste in the United States

Of the 38.4 million tons of food waste generated in the U.S. annually, only 2.2% is recycled or composted (USEPA, 2016a). As a result, food waste accounts for the single largest component (21.6%) of municipal solid waste material in landfills adding, representing about 29 million tons (Figure 1; USEPA, 2016a). Thus, food waste recovery efforts are minimal compared with other municipal solid waste recovery such as paper (64% recovery), household yard waste, as well as metal (34% recovery) and plastic containers (USEPA, 2016a),.

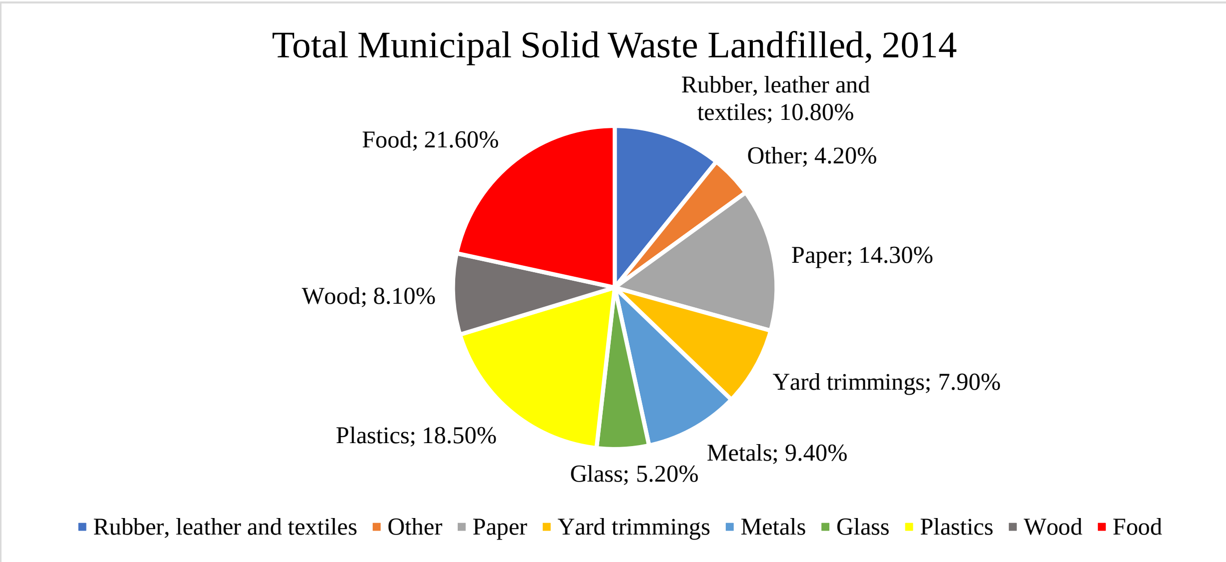

Figure 2. Distribution of solid waste materials that are disposed in landfills; adapted from USEPA, 2016a

In 2010, the United States Environmental Protection Agency (US EPA, 2010) proposed the food waste recovery hierarchy in order to prioritize solutions to prevent and divert wasted food to higher value purposes (Figure 2).

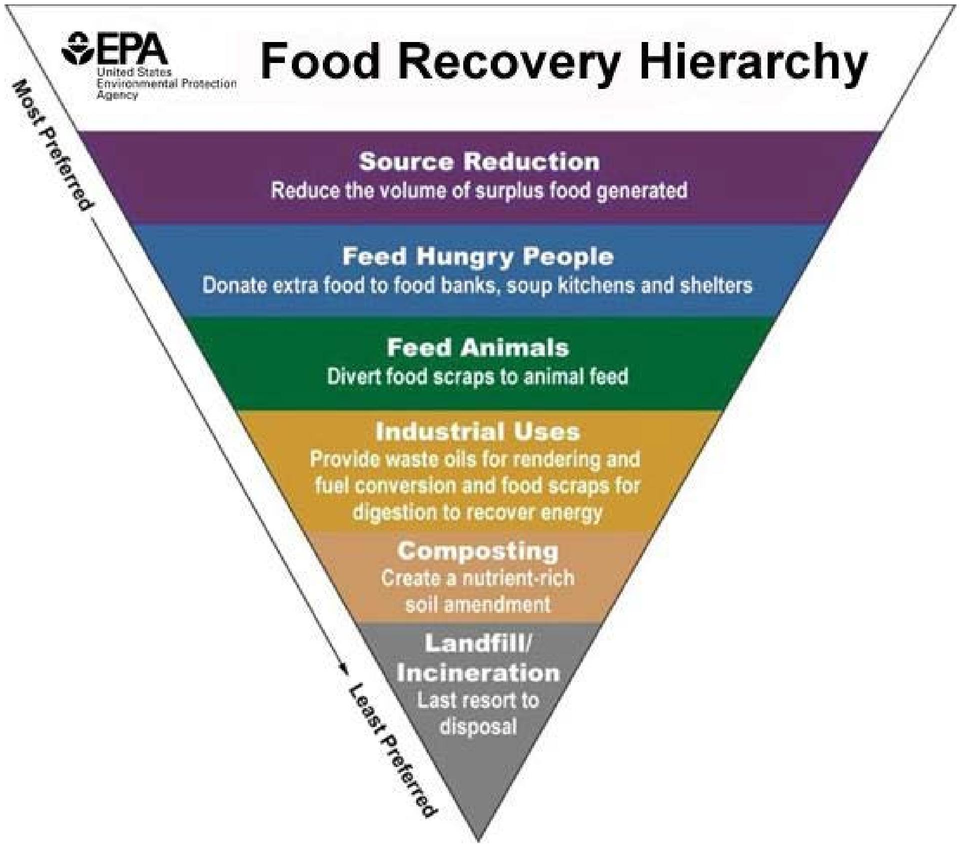

Figure 2. Food recovery hierarchy proposed by the U.S. EPA (2010).

Within the food waste recovery hierarchy proposed by the U.S. EPA, there are 5 proposed solutions to re-purpose food waste for high value uses and minimize disposal by landfilling and incineration, which are the least valuable methods. These higher value alternative options (ranked from greatest to least value) include source reduction, providing donations to feed hungry people, converting into animal feed, industrial energy recovery, and composting. Based on three dimensions of sustainability which include environmental, economic, and social impacts, Papargyropoulou et al. (2014) concluded that prevention of surplus food generation is the most attractive option followed by food waste donation and conversion to animal feed. These recommendations are in agreement with the recommendations proposed by the U.S. EPA (Papargyropoulou et al., 2014).

In addition to the top three most favorable options for food waste management, biogas production from anaerobic digestion for energy recovery and composting are also desirable options compared with landfilling because these options minimize greenhouse gas production (Adhikari et al., 2008; Levis and Barlaz, 2011; Zhang et al., 2007). Zhang et al (2007) investigated the potential use of food waste as a feedstock in anaerobic digestion, and showed that food waste can be a highly desirable material because of its high biodegradability and a carbon to nitrogen ratio of 14.8, with high biogas yield and methane accounting for 73% of total gas production. Finally, composting is the least desirable food waste management solution before landfilling. However, composting has been the second most common practice to manage food waste because it is relatively simple to do compared with the equipment cost and more extensive processing required when converting into animal feed or use in anaerobic digesters. The U.S. EPA estimated that about 1.5 million tons of materials were composted in 2013 using data collected in 35 different states (EPA, 2016a). Composting of food waste offers some nutrient recovery through microbial degradation when food waste is mixed with soil (Lee et al ., 2004). Composted food waste can then be used to provide organic matter and valuable nutrients to enrich the soil for agricultural purposes. Studies have shown that food waste can be a suitable material for composting due to the high organic matter content and low concentrations of heavy metals (Yang et al., 1998; Lee et al, 2004). The resulting compost can then be used to enrich soil nutrients and act as alternatives to chemical fertilizers (Lee et al., 2004).

In summary, the food waste recovery hierarchy provides solutions to minimize the environmental impact of food waste and retrieve greater value from food that is already produced but not consumed, and feeding food waste to animals is the most favorable solution once the food waste can no longer be used for human consumption (Papargyropoulou et al., 2014).

4. Global efforts on converting food waste to animal feed

In the United States, feeding food waste to swine historically was done to a limited extent in rural locations near major metropolitan areas, with more than 2,200 “garbage feeders” licensed in the United Sates (Westendorf, 2000). Currently, there are approximately over 2,100 licensed swine operations capable of feeding cooked food waste (EPA, 2014). Major categories of food waste that been fed to pigs include post-preparation and consumption food scraps, bakery waste, expired foods from grocery stores, and post-consumer waste produced from multiple sources such as restaurants, households and schools (Westendorf, 2000). According to the United States Department of Agriculture (USDA), the practice of “garbage feeding” is defined as “material consisting in whole or part of animal waste resulting from handling, preparing, cooking, and consuming food, including the offal parts” (United States Congress, 1980). In 1980, the U.S. federal government established the Swine Health Protection Act (SHPA) which outlined an approved protocol for feeding food wastes to pigs (Gamble, 1998). This Act was proposed to “protect the commerce of the United States and the health and welfare of the people of the United States by ensuring that food waste fed to swine does not contain active disease organisms that pose a risk to U.S. swine ” (United States Congress, 1980). Furthermore, this Act mandated that “all such food must be boiled before being fed to hogs and those facilities conducting the boiling must be registered with either the USDA or the chief agricultural or animal health official in the state in which the facility is located" (United States Congress, 1980). Therefore, this act provided a clear framework and guidelines for the farmers who commonly feed food waste to their pigs and also set up a health protection barrier for the consumers. However, regulations may vary from state to state in which some states have banned food waste donations for animal feed while others regulate the types of food waste that can be used. The protocols may also require specific treatment processes in order to comply with regulations for providing food waste to food animal producers. According to the regulations described in the Swine Health Protection Act, food waste was also mandated to be treated before feeding: "Food waste shall be heated throughout at boiling (212°F or 100°C at sea level) for at least 30 minutes; and it shall be agitated during cooking, except in the steam cooking equipment, to ensure that the prescribed cooking temperature is maintained throughout the cooking container for the prescribed length of time" (United States Congress, 1980). The heat treatment process can include direct fire or steam injection methods (United States Congress, 1980). The direct fire method requires that the facility use a flame to provide heat so that it comes in direct contact with a container, and the contents should be mixed frequently. For facilities that have higher processing capacity, the steam injection method can be used, which involves introducing steam into the bottom of a load of food waste so that it is uniformly heated as steam percolates throughout the container (Westendorf, 2000).

Furthermore, in 2011, the FDA implemented the Food Safety Modernization Act (FSMA) which specifically addressed the act of feeding food scraps to animals in the

Preventative Controls for Animal Food Rule. The rule mainly focuses on “by-products from human food facilities are commonly used as animal food, including as animal food ingredients. While these by-products may not be suitable or desirable for human consumption, they may be suitable as a source of energy and nutrition for certain species of animals” (Murphy, 2016). The rule requires processing facilities to implement production safety controls such as Hazaard Analysis and Risk-based Preventative Controls (HARPC) and Current Good Manufacturing Practices (CGMPs).

Currently, a number of organizations in the United States have been promoting the use of food waste in animal feed. For example, a collaboration group formed by businesses, non-profit organizations, and government leaders named “Rethinking Food Waste Through Economics and Data” (ReFED), has evaluated the potential of diverting food waste into animal feed using data collected from key stakeholders and research publications to account for regional economic variations. Results from using the ReFED model showed that after accounting for the food waste materials that have already been reused for other purposes, there is a diversion potential of 49,000 tons of appropriate food waste materials out of a total of 3.6 million tons of food waste from retail, wholesale, and industrial sources that can be used for animal feed, which could reduce greenhouse gas emission by 34,000 tons (ReFED, 2016b). ReFED has also created the Food Waste Policy Finder for food businesses to help decision makers better understand the regulations and best practices for divert their food waste into higher value uses. In addition to ReFED, the Harvard Food Law and Policy Clinic and the Food Recovery Project at the University of Arkansas has also published the first-ever catalogue of different state regulations and requirements for feeding food waste to animals, and provides useful legal information for stakeholders to consider when utilizing their food waste as animal feed. On a practical basis, one of the largest national retailers (Walmart) has been diverting 60% of their organic waste to animal feed (Worley, 2014). From a survey conducted by the Food Waste Reduction Alliance (FWRA), using data provided by participating food industry organizations including the Grocery Manufacturers Association, Food Marketing Institute and National Restaurant Association, it is estimated that out of all the surveyed facilities, 82.4% of food waste generated from the manufacturing sector (16 surveyed), 11.1 % from the retail/wholesale (13 surveyed) and 0.02% from the restaurants (27 surveyed) were used as animal feed (EPA, 2015). However, these numbers only accounted for the respondents who participated in the survey and cannot be extrapolated to the entire U.S. because of the limited number of participants in this survey. However, the objective of the survey was to gain a better understanding of the quantity of food generated, diverted, and disposed by different sectors in the food industry. This was a voluntary survey conducted by the Food Waste Reduction Alliance (FWRA), which is an initiative formed by three major food industry associations including the Grocery Manufacturers Association, Food Marketing Institute, and National Restaurant Association, with the goals of reducing the amount of food waste generated, increasing the amount of safe, nutritious food donated to those in need, and recycling unavoidable food waste. Membership in FWRA includes chain restaurants (e.g.The Cheesecake Factory, McDonald's), chain grocery stores (e.g.Target, Safeway), and major food manufacturers (e.g. Tyson Foods, Inc. and Campbell's).

In Minnesota, the Minnesota Technical Assistance Program (MnTAP) funded by the Minnesota Pollution Control Agency (MPCA) assists local businesses to reduce wasted resources and prevent pollution by providing industry-tailored technical solutions. The MnTAP focuses on four major areas including air, energy, waste, and water related to pollution impacts and efficiency. For recycling food waste to animal feed, the MnTAP program provides a contact reference list and information to local businesses that would like to donate their food waste for animal feed usage.

Globally, many countries and organizations have also been promoting the use of food waste in animal feed. In Japan, food waste from the food processing and catering industries, as well as households, is being recycled as Ecofeed (Sugiura et al., 2009). There are 171 Ecofeed producers in Japan, which are certified by the Japan Scientific Feed Association (JSFA), and provide 150,000 metric tons of Ecofeed annually (Sugiura et al., 2009). In China and Vietnam, the French National Institute for Agricultural Research (INRA) GloFoods Meta-program has funded the “blue barrels” project, with aims to study the collection and recycling of urban food waste in peri-urban livestock farms in China and Vietnam (Duong, 2016). In Europe, the European Union’s Seventh Framework Program for Research and Technological Development provided 3 million euros in funding for the NOSHAN (Sustainable Production of Functional and Safe Feed from Food Waste) project in 2012, with the aim of investigating processes and technologies needed to use food waste for feed production at low cost, low energy consumption, and maximize economic value of starting waste materials (Community Research and Development Information Service Europe (CORDIS), 2016). The European Union’s Horizon 2020 Framework Program has also funded the “Resource Efficient Food and Drink for the Entire Supply Chain”(REFRESH) project which proposed a web based application for food businesses to determine whether their surplus food waste can be fed to animals based on legislation and legal requirements of the user's local government (Luyckx, 2017). Thus, adaptation of food waste to animal feed is recognized globally by government agencies and private organizations as an important attempt to overcome the challenges of the enormous amount of food waste currently being produced.

5. Benefits and limitations of food waste for animal feeding

Recycling food waste into animal feed not only has numerous benefits to the environment and economy, it can also improve the sustainability of our food production system. Using food waste as animal feed can reduce the competition for using grains in livestock feed instead of human food. Currently, about 75% of all agricultural land in the world is associated with food animal production, with about 36% of the total calories produced from crops being used in animal feed rather than for human foods (Cassidy et al., 2013; Foley et al., 2011). This competition for grains between humans and food producing animals places high demands and expectations on crop production systems, and has created controversy over the relative inefficiency of converting these calories to meat as well as the long-term sustainability of our food production system (Cassidy et al., 2013).

It is estimated that growing crops exclusively for human consumption can potentially increase the availability of food calories by 70%, which could feed an additional 4 billion people in the future based on their dietary caloric needs (Cassidy et al., 2013). Recent research has shown that reducing animal feed produced from arable land would have positive effects on the environment by reducing greenhouse gas emissions by 18% and creating a nitrogen surplus of 46% (Schader et al., 2015). However, this scenario is only valid when all the animals are fed using pastures and by-products from food production. However, these result show that reducing the use of feed components that do not directly compete with human consumption can potentially increase the sustainability of food animal production.

In contrast, the food animal production industry has historically, and continues to use of edible food by-products not suitable for human consumption in animal feeds. Examples of these by-products include grain-based by-products (e.g wet and dried distiller's grains, corn gluten meal, corn gluten feed, wheat bran), food industry by-products (e.g. bakery waste, cannery waste, restaurant waste), rendered animal by-products (e.g. meat meal, meat and bone meal, blood meal, poultry meal, choice white grease, tallow, poultry fat), and other plant-based by-products (e.g. citrus pulp, almond hulls). Because these by-products are not suitable for human consumption, they pose no direct competition to human consumption (Capper et al., 2013). In ruminant systems, forage crops such as pasture grasses, alfalfa, and clover are a major source of ruminant diets but these crops are not suitable for human consumption (Capper et al., 2013). Furthermore, foods produced by animals are concentrated sources of energy and nutrients, which result from feeding cereal grains and by-products to animals, which provides high quality protein and other essential nutrients to humans (McNeill et al., 2017). Protein of animal origin has a much better amino acid profile that more adequately meets human amino acid requirements compared with the amino acid profile from plant origin, and meat also provides greater amounts of bioavailable nutrients such as iron, zinc and essential vitamins to meet the nutritional needs of humans (Elmadfa and Meyer, 2017; McNeill et al., 2017). Therefore, it is important to understand that there are many complexities involved when considering the relative competition between human food and animal feed. Nevertheless, using food waste in diets of food producing animals can improve the sustainability of our food system and reduce the negative environmental impacts of food animal production.

On the other hand, in spite of the great benefits of food waste being used as animal feed, it also has limitations. One of the major concerns of food waste feeding is related to the potential risk of biological hazards, such as transmission of pathogens that can cause disease when food waste is not properly heated when fed to swine. Some pathogens can be spread in contaminated food waste to animals on farms, and potentially to humans if pigs consume improperly heated contaminated food waste (Westendorf, 2000). For instance, *Trichinellosis* was one of the most devastating parasites in pigs and humans in the early 1930's to 1950's associated with the feeding of food waste containing meat scraps (Zimmerman et al., 2012). The disease is caused by the ingestion of raw or undercooked animal tissues infected with the parasitic nematode *Trichinella sprialis.* Following the ingestion of infected materials, the *Trichinae* larvae then undergo complete development within the host in 17 to 21 days. After completing their life cycles, male and female adult parasites then mate and produce newborn larvae in the host which leave the intestine and migrate through the circulatory system to striated muscle tissue. There, they penetrate the muscle cells, modify the cells to become unique cysts, and mature to become infective for another host (Gamble and Murrell, 1998). Consequently, the parasite can be spread uncontrollably within a swine operation once a portion of pigs are infected, resulting in reduced profits of the farms, and can infect humans consuming undercooked meat from these animals (Gamble and Murrell, 1998). When humans consume trichinae contaminated pork, abdominal discomfort and diarrhea will occur within one or two days following ingestion. Then, muscle aches, fever, chills, and joint pain will occur at about 2 to 8 weeks after ingestion (Davis, 2016). However, the parasite can be destroyed by proper cooking and storing of the pork. Cooking pork at least for 10 minutes at a temperature less than 58.5°C or freezing the meat at -20°C for 3 days can completely destroyed the parasite. Furthermore, the United States pork industry is now free of Trichinella and the detection of positives cases have been maintained at 0% (Gamble and Murrell, 1998). In addition to Trichinella, pathogens such as E.coli and Salmonella can also be a risk factor to swine when practicing food waste feeding. However, these pathogens can be inactivated by proper processing of the food waste, where E.coli can be inactivated by heat treatment at 65°C for 20 minutes and Salmonella can be inactivated by heat treatment at 80°C for 30 minutes (Duong, 2016)

In addition, other non-zoonotic diseases such as classical swine fever, foot and mouth disease, African swine fever, and swine vesicular disease are currently not present in U.S. swine herds, but were a potential threat to the pork industry before implementation of eradication programs (Westendorf, 2000; Zimmerman et al., 2012). For instance, in the early 1900's, classical swine fever was a devastating disease in the U.S. swine industry because it can rapidly spread through farms and dramatically increase mortality. Yet, through an eradication program mandated by law and regulated by the Agricultural Research Service, the United States was able to achieve elimination of classical swine fever in 1974, and was officially declared free of this disease in 1976 (FAO, 2000). For this reason, federal regulations of garbage feeding were established in the U.S. in order to reduce the risk of pathogen transmission and disease outbreak by enforcing laws for farmers to strictly comply with the regulations, many of these diseases have been eradicated or cases of infection have been greatly reduced over the past 20 years. For example, in 2011, the estimated prevalence of *Trichinella* in the U.S. commercial pig herd is less than 0.194 per million at a 95% confidence level and less than 0.296 per million at a 99% confidence level (Wilson et al., 2015).

Table 1. Nutritional composition (dry matter basis) of food waste fed on sample farms (Westendorf, 1999)

Item	Sample Size	Mean	Standard Deviation	Coefficient of Variation	Range
Dry Matter,%	63	27.0	5.2	19.3	13.0 to 39.6
Crude Protein,%	63	20.8	5.7	27.5	13.6 to 37.7
Crude Fat,%	63	26.3	8.0	30.4	9.1 to 46.9
ADF[1] ,%	62	6.3	2.6	41.2	2.4 to 15.3
Ash,%	63	6.2	2.2	35.3	3.0 to 16.4
Ca,%	63	0.92	1.02	111.1	0.06 to 6.33
P,%	63	0.64	0.46	72.1	0.12 to 2.18
Mg,%	63	0.08	0.03	34.8	0.03 to 0.13
Na,%	63	1.04	0.37	35.5	0.63 to 1.79
K,%	63	0.83	0.43	51.6	0.13 to 2.01
Cu, mg/kg	54	17.3	23.5	136.4	1.4 to 164.6
Fe, mg/kg	63	441	314	71	78 to 1,778
Zn, mg/kg	63	63	201	321	10.6 to 1,621
Mn, mg/kg	54	21.0	15.6	74.4	5.7 to 58.4

[1]Acid detergent fiber

In addition to the concerns of pathogen transmission, another drawback of utilizing food waste as animal feed is the lack of consistency and uniformity. According to a research study conducted at Rutgers University, wet food waste fed to hogs from sampled farms can be highly variable (Westendorf, 2000). Westendorf (2000) collected food waste samples from multiple farms in New Jersey in order to characterize the nutrient composition and variability of commercial food waste for swine feed. The samples represented food waste from different sources such as restaurants, casinos, military bases, hospitals and nursing homes, which were blended with food waste from bakery by-products, fish canneries, or vegetable processing waste. These samples were analyzed for nutrient composition and the data are shown in Table 1. The nutrient composition of the samples collected was highly variable, as indicated by the high coefficient of variation. This variability in nutrient composition is a major challenge for use in commercial swine feeding programs that require precisely matching nutrient supply of the diet with the nutrient requirements of pigs being fed those diets.

6. Use of food waste in swine diets: Nutrient composition, growth performance, and carcass characteristics

Several studies were conducted in the late 1990's and early 2000's investigating the inclusion of food waste from multiple sources into swine diets. One study conducted at the University of Florida in 1999, utilized food waste from a restaurant at a resort complex in central Florida to perform 2 feeding experiments. The experiments compared the effects of inclusion of dehydrated food waste in corn and soybean meal diets on growth performance and carcass composition of growing-finishing pigs weighing at 55 to 110 kg (Myer et al., 1999). These researchers blended the dehydrated food waste with soybean hulls, wheat flour, or corn in both trials (55:45 blend of soybean hulls and surplus wheat flour for experiment 1 and 67:33 blend of soy hulls and ground corn for experiment 2). The food waste blends (FWB) were then further mixed with ground corn and soybean meal to create different diets that contained a similar ME to digestible lysine ratio, with one diet containing 0% food waste blend (87.15% ground corn and soybean meal as major energy and amino acid sources) and one diet containing 40% food waste blend (as energy source substitute) in experiment 1. In experiment 2, 0%, 40% and 80% of food waste was blended with corn and soybean meal for the experimental diets. A comparison of the average nutrient composition of these food waste blends with that of soybean meal and corn is shown in Table 2.

Table 2. Composition of dehydrated food waste blends in used in Experiment 1 and 2 (as-fed basis; Myer et al., 1999)

	Ingredients			
	Food waste blend		**Feedstuffs**	
Nutrient, %	**Experiment 1**	**Experiment 2**	**Soybean meal**	**Corn**
Moisture	11.4	8.4	12.2	11.2
Crude protein	15.0	14.4	48.1	8.9
Crude Fat	13.8	16.0	1.1	3.5
Crude Fiber	10.3	14.5	3.4	2.1
Ash	5.8	4.7	6.5	1.1
Ca	0.54	0.63	0.29	0.02
P	0.34	0.38	0.71	0.26
Soluble Cl	0.69	0.86	<0.02	0.05
K	0.55	0.80	2.20	0.32
Na	0.35	0.47	<0.01	<0.01

As shown in Table 1, the chemical analysis of the FWB showed several important nutritional characteristics compared with tradition feed ingredients used in these experimental diets. First, the FWB was low in moisture and high in crude fat, while also being moderately high in crude protein, crude fiber and ash (Myer et al., 1999). After subtracting the nutrient contributions provided by the corn and soybean meal that were mixed into the FWB, the FWB composition was estimated to be 24 to 26% crude fat, 18 to 20% crude protein, 4 to 7% crude fiber, 5 to 6% ash, 0.5 to 0.8% Ca, 0.3 to 0.8% P and

2.0 to 2.5% salt on a dry matter basis (Myer et al., 1999). Chemical composition values obtained from FWB were reported to be similar with the values obtained from a previous study (Myer et al., 1994).

In addition to considering the nutrient composition of food waste, growth performance and carcass characteristics of pigs fed diets containing food waste was the next step in evaluating the feeding value of food waste for swine. Results from both experiment 1 and 2 showed that overall growth performance of the pigs was not affected by the addition of up to 80% food waste blend to corn-soybean meal diets when fed nutritionally balanced diets (Table 3).

Table 3. Growth performance of finishing pigs in experiment 1 and 2 (Myer et al., 1999)

Experiment	**1**		**2**		
Food waste blend, %	0	40	0	40	80
Average daily gain, kg	1.01	1.01	0.91	0.91	0.90
Average daily feed intake, kg	3.38	3.00	2.98	2.88	2.67
Gain:feed	0.30	0.34	0.31	0.32	0.34

The inclusion of the FWB up to 80% of the diets resulted in no change in average daily gain, but gain to feed ratio in both trials was improved by including FWB in the diets. This response was likely due to the higher fat and ME content of the FWB diets shown in Table 2 (Myer et al., 1999).

The carcass characteristics of pigs fed the food waste diets are shown in Table 4. Carcass characteristics (back-fat thickness, longissimus muscle area, percentage of carcass lean, loin color, loin firmness, and loin marbling) were not affected by the inclusion of the FWB in the diets. However, carcass fat firmness score increased when pigs were fed up to 80% FWB diets compared with those fed the control diet in experiment 2. This difference was likely due to the relatively high level of polyunsaturated fatty acids in the lipids contained in the FWB (Myer et al., 1999) resulting in softer carcass fat when the dietary inclusion of FWB increased.

Table 4. Carcass characteristics of growing-finishing pigs fed diets containing dehydrated food waste in Experiment 1 and 2 (Myer et al., 1999)

Experiment	**1**			**2**			
Food waste blend, %	**0**	**40**	**SEM[a]**	**0**	**40**	**80**	**SEM[b]**
Backfat, cm	2.6	2.4	0.2	2.7	2.5	2.3	0.05
Longissimus muscle area, cm^2	37.4	38.6	0.73	34.8	35.6	34.3	0.42
Carcass lean, %	49.3	50.6	0.70	48.5	49.8	49.7	0.32
Loin color score [c]	2.9	2.9	0.08	2.6	2.3	2.4	0.1
Loin firmness score [d]	2.7	2.7	0.12	2.5	2.6	2.4	0.06
Loin marbling score [e]	2.8	2.4	0.25	2.3	2.3	2.2	0.1
Carcass fat firmness score [f]	1.4	1.7	0.16	1.5	2.2	2.6	0.12

[a]Standard error of the mean n = 4 pens of 6 pigs each
[b]Standard error of the mean n = 3 pens of 8 pigs each
[c]Scores of 1 to 5: 1 = pale 2 = grey, 3 = light pink, 4 = reddish pink 5 = Dark pink
[d]Scores of 1 to 5: 1 = very firm 2 = firm, 3 = slightly firm, 4 = slightly soft 5 = soft
[e]Scores of 1 to 5: 1 = slight 2 = traces, 3 = slight, 4 = modest 5 = high
[f]Scores of 1 to 4: 1 = firm, 2 = slightly soft, 3 = soft, 4 = very soft, oily

A similar study was conducted at the Rutgers University in 1998, in which growing-finishing pigs were fed cooked food waste collected at a student cafeteria to compare growth performance, nutrient digestibility, and meat quality with pigs fed corn and soybean meal control diets (Westendorf et al., 1998). However, instead of blending food waste with other feed ingredients as was done in the Myers et al. (1999) experiments, the food waste in this study was directly fed to the pigs after collection Results from this study showed that pigs fed food waste gained slower during the growing phase but growth rate was not different in the finishing phase compared with pigs fed the corn-soybean meal control diets. The dry matter digestibility was similar between the control and food waste diets, while crude protein digestibility was found to be greater in the food waste diet compared to the corn-soybean meal control diet. Lastly, meat quality and flavor was found to be acceptable when evaluated by a consumer panel, and was not different from pork from pigs fed the corn-soybean meal control diets. Thus, the author concluded that feeding this source of dehydrated food waste to growing-finishing pigs is an acceptable feed ingredient (Westendorf et al, 1998).

Jones et al. (2004) also investigated the effect of feeding dried food waste at a 20% inclusion rate in growing pig diets on the growth performances and nutrient digestibility of growing pigs. Similar results were observed from previous studies indicating that there were no differences in growth performance or nutrient digestibility when feeding the 20% food waste diet compared with the control corn-soybean meal diet. As a result, these researchers suggested that the addition of 20% processed food waste to commercial swine diets is acceptable (Jones et al., 2004).

In addition to studies utilizing food waste generated in the United States, there have also been studies conducted in Norway on the effect of feeding food waste to growing pigs. Researchers at the Agricultural University of Norway conducted an experiment on feeding 0, 20, 40, 60 , 80 and 100% food waste products to growing-finishing pigs to evaluate the effect on growth performances, carcass characteristics, and meat quality (Kjos et al., 2000). Food waste used in this study was a mixture of many different food waste sources such as bakery, dairy, ice-cream factory, slaughterhouse, and pizza factory. The composition averaged 21% DM, 4.9% CP, 3.3% EE, 1.2% ash. The food waste was mixed with barley and soybean meal on a net energy basis to produce 6 dietary treatments of 0, 20, 40, 60, 80 and 100% food waste. Results from the study showed that diet inclusion rate of food waste had no effect on ADG, and ADFI and feed to gain ratio linearly decreased as the inclusion rate increased (Kjos et al., 2000). Authors concluded that the feeding this mixture of food waste had no adverse effect on the growth performances of growing-finishing pigs. However, feeding increasing levels of food waste linearly reduced fat firmness in the carcass due to the increasing PUFA intake with increasing dietary levels of food waste. In addition, high inclusion level of food waste products (80% and 100%) was also found to increase drip loss percentage and reduce the lightness of color of meat. Inclusion rate of 40% or higher food waste product was also found to linearly increase the PUFA content of carcass backfat. Finally, the authors concluded that this food waste mixture has the potential to be used as a feedstuff in growing-finishing pig diets with optimal inclusion range of 20 to 60% (Kjos et al., 2000).

Similarly, several studies have also been conducted in Korea to investigate the potential of feeding recycled food waste (dried food waste from restaurants and apartment complexes) to pigs. Results from Nam et al., (2000) suggested that out of the 3 inclusion levels investigated(0%, 30% and 50%), 30% inclusion of food waste in the diets did not affect the growth performance and carcass characteristics of the pigs compared with feeding control diets (Nam et al, 2000). Chae et al. (2000) found that feeding dried food waste had a linear effect on the ADG and feed to gain ratio of the pigs as the inclusion level of food waste increases from 0 to 20% and 20 to 40%. However, carcass characteristics were found to be not affected by the treatments. The authors concluded that the optimal inclusion level of dried food waste in the diets should be approximately 20% for growing-finishing pigs based on performances of growth (Chae et al., 2000). In addition to growth performances and carcass characteristics, these studies have also investigated the nutrient digestibility of the food waste products. Nam et al. (2000) reported that digestibility of crude fat and crude fiber in the 30% food waste diet did not differ from the control diet, while CP and crude ash were found to be less digestible in the 30% food waste diet. In contrast, Chae et al., 2000 reported that the digestibilities of CP and crude fat were higher in the 20% and 40% dried food waste diets when compared with the control diet. Yet, the digestibilities of energy, ash, Ca and P was found to be lower in the dried food waste compared to the control.

In summary, the results from several previous studies from around the world show that various types of food waste can be added to swine diets at relatively high dietary inclusion rates with minimal or no effects on the growth performance, carcass composition, and meat quality of pigs. Thus, it is necessary to continue to further evaluate various new types of food waste sources using current feed formulation procedures and feeding applications in commercial pork production systems.

7. Future challenges and opportunities of using food waste as animal feed

Theoretically, food waste from a wide variety of sources can be transformed and used as animal feed (Wlcek and Zollitsch, 2004). However, processing of food waste materials into animal feed requires acceptable equipment and facilities to comply with feed safety regulations and preserve nutritional value. Thus, in order to promote the recycling of food waste in to animal feed, the following diagram provides a description of motivations and possible business models if food waste were to be commercialized as animal feed (Figure 3).

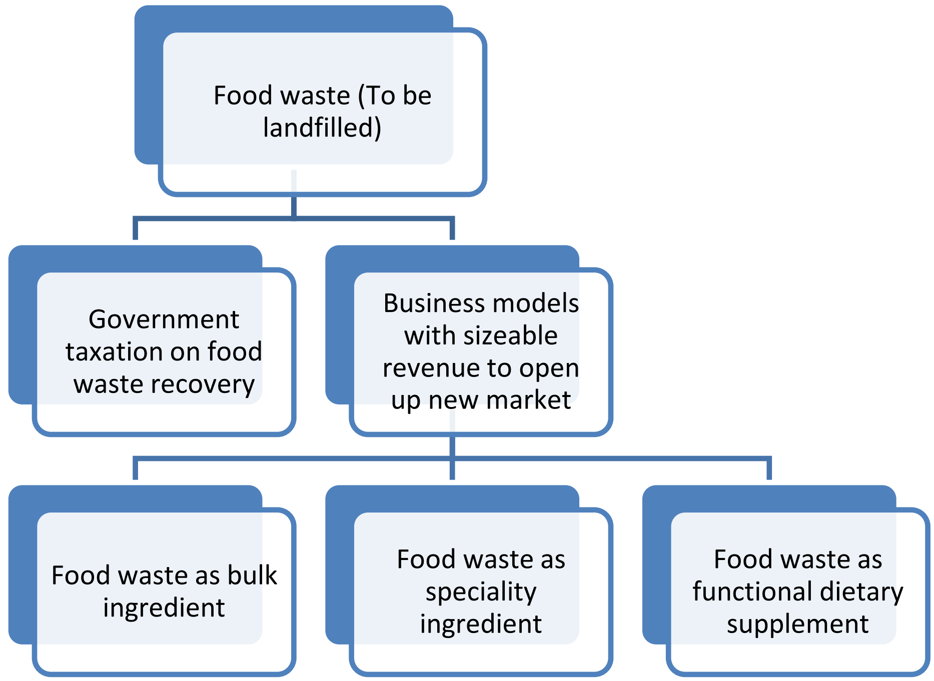

Figure 3. Conceptual map of motivations to promote food waste to animal feed conversion

Compared to government taxation which directly puts economic and political pressure on the stakeholders, three different business models can potentially be developed to attract interest in food waste recovery and conversion into animal feed, and some of these strategies have already been implemented by companies and shown to be successful. For example, food waste can be utilized as a bulk ingredient to replace other common energy and nutrient-providing feed ingredients such as corn and soybean meal which comprise the majority of complete swine diets. An example of this approach is the formation of ReConserve® Inc. (Santa Monic, CA). This company produces DBP® (dried bakery product) from bakery and snack waste from the food industry which can be used as major energy source in swine diets up to a 30% inclusion rate. However, the idea of using other food waste materials such as supermarket and restaurant food waste to produce a stable bulk ingredient can be challenging due to the variability in composition and nutrient content of the sources being used. If the energy and nutrient composition is highly variable, it is difficult to accurately formulate diets and the risk of overfeeding and underfeeding nutrients to animal is increased. This challenge can be overcome when sufficient data are established to allow the development of prediction equations and in-vitro assays to quickly quantify the energy and digestible nutrient content of the food waste sources fed (Messad et al., 2015; Święch, 2017).

Furthermore, the price of dehydrated food waste must be competitive with other common ingredients, such as corn and soybean meal, in order to be considered as a viable, cost effective alternative feed ingredient. Producing heat-processed food waste at a cost competitive price may be challenging because of the capital investment and operating costs of processing. On the other hand, food waste can also be used as specialty ingredients to provide specific essential nutrients in animal rations. International Ingredient Corporation (St. Louis, MO) collects food waste from the cheese and candy industry and generates specialty feed that provides lactose and simple sugars in nursery pig diets. This business model requires precise targeting of high quality, consistent, and well characterized food waste materials from the food industry in order to meet nutrient guarantees in the final products.

Finally, another possible option is to transform components of food waste into a functional dietary supplement in animal diets. Functional nutrients are characterized as having a unique function and specific purpose to support the animal health and growth performance such as providing a prebiotic effect from unique fiber composition (Lindberg, 2014; Reese, 2003). However, this business model requires further efforts in the research to identify and extract the targeted functional nutrients from the selected food waste in sufficient amounts for commercialization. As a result, at least 3 types of applications and business models can be developed for recycling food waste into animal feed.

In summary, immediate actions are certainly needed to re-purpose food waste into higher value uses to protect our society from devastating economic and environmental losses. It is essential for researchers to clearly identify the classification of food waste they are referring to and specifically target the source(s) of food waste that bring value to animal diets and are produced in large quantities to justify investment in processing and marketing. Previous studies have consistently suggested that food waste can be a suitable alternative feed ingredient in swine diets because of their rich energy and digestible nutrient content resulting in achieving acceptable growth performances and meat quality. Utilizing food waste as animal feed provides benefits to both the general public and the pork industry because it improves the sustainability of our food system and minimizes the negative impacts of food waste disposal in landfills. Different business models can provide useful guidelines for entrepreneurs to consider when developing companies and infrastructure to collect and process food waste into animal feed. However, up-to-date nutritional data and feeding studies are needed to guide nutritionists in evaluating the economic and nutritional value of using food waste as animal feed. Thus, the focus of the research described in this thesis is to identify suitable stream(s) of food waste to be used as swine feed and investigate their nutrient content, feeding value, and environmental impacts.

Chapter 2

Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs

Published as:

Fung, L., P. E. Urriola, L. Baker, and G. C. Shurson. (2019). Estimated energy and nutrient composition of different sources of food waste and their potential for use in sustainable swine feeding programs. Translational Animal Science, 3(1), 359-368. https://doi.org/10.1093/tas/txy099

Abstract

About 40% of the total food produced in the United States is wasted at multiple stages throughout the supply chain. The objective of this study was to determine the energy and nutrient content and variability of food waste sources generated at different stages within the food supply chain in the Minneapolis-St. Paul, MN metropolitan area, and their potential for use in swine diets. A total of four waste sources were selected: supermarket (SM; retail to consumer), university residential dining hall (RH; consumer to post-consumer), a city waste transfer station (TS; post-consumer to municipal waste disposal), and household source separated organic recycling program (SSO; post-consumer to municipal waste). Samples were collected and analyzed for gross energy (GE), proximate analyses, minerals, amino acids, and fatty acid concentrations along with lipid peroxidation indicators including peroxide value (PV) and thiobarbituric reactive substances (TBARS). Data were analyzed using a general linear model that included food waste source as the main factor, and least squared means with adjustment were used for multiple comparisons. Samples of SM food waste contained the greatest (P < 0.05) concentration of GE (5909 kcal/kg) compared with RH, TS and SSO sources. Calculated net energy (NE) of SM (3,740 kcal/kg) was also the greatest compared with the 3 other food waste sources. Food waste from SM, RH and SSO, but not TS, had greater (P < 0.05) calculated NE than published values for corn and soybean meal. Concentrations of Lys (1.82%), Met (0.53%), Thr (1.07%) and Trp (0.27) content were greater in SM than in RH, TS and SSO, but these concentrations were less than published values for soybean meal. There were no differences (P > 0.05) in the phosphorus content of samples among food waste sources (0.30% to 0.64%). Peroxide value and TBARS were greatest (P < 0.05) in the SSO samples (PV = 82.4 meq/kg oil; TBARS = 2.44 mg MDA eq/g oil) compared with the other 3 food waste sources. Although the concentrations of nutrients and calculated energy values of the food waste sources were moderately high compared with corn and soybean meal, their composition was highly variable. Food waste generated upstream (SM) in the food supply chain appears to have greater nutritional value than post-consumer food waste (RH, TS and SSO), but all sources appear suitable for use in commercial swine diets provided that ME, NE, and nutrient digestibility values are well characterized.

Keywords: amino acids, energy, food waste, nutrients, phosphorus, swine

Introduction

Food price increases in recent decades have led to discussion on the need to increase agricultural productivity and reduce food waste to ensure food security (Von Braun and

Braun, 2008). However, most of the focus has involved developing and implementing new technologies to increase agricultural productivity, with much less attention being devoted to managing the 40% of the food waste generated annually in the United States (Gunders, 2012). Since 1974, food waste in the United States has increased by approximately 50%, and is responsible for 25% of fresh water, and 300 million barrels of crude oil consumption annually (Hall et al., 2009). Not only does this enormous amount of food waste lead to significant economic losses, it also causes significant negative social and environmental impacts due to inefficient use of natural resources and the production of greenhouse gases, such as carbon dioxide and methane from landfills which are extensively used for food waste disposal (Adhikari et al., 2006; Hall et al., 2009). Therefore, alternative methods to divert food waste into higher value uses are needed to minimize their environmental impact and promote long-term sustainability of our food system (Dorward, 2012).

Generation of food waste occurs at multiple stages of the food supply chain beginning at production, followed by transportation, handling, storage, processing, packaging, distribution, marketing, consumption, and post-consumption (Lipinski et al., 2013; Parfitt et al., 2010). Within each of these stages, several major food waste generation sources include processing facilities, restaurants, schools, public institutions, grocery stores, and households (Gustavsson et al., 2011).

Limited information has been published previously regarding the chemical characteristics and nutritional value of various sources of food waste and their potential use in animal feeds, and only a few studies have previously investigated the growth performance of pigs fed specific food waste sources (Myer et al., 1999; Westendorf et al., 1998). Therefore, the objective of this study was to characterize the nutritional composition of major food waste sources in the Minneapolis-St. Paul, MN metropolitan area and their potential for use in swine feeding programs. We hypothesized that food waste generated upstream in the food supply chain provides greater nutritional value due to less contamination with other waste materials (e.g. paper and plastic) than downstream food waste sources.

MATERIALS AND METHODS

Food Waste Sources

Four food waste sources representing different food waste generation segments in the food supply chain were identified in the Minneapolis-St. Paul, MN Metropolitan area including retail to consumer (i.e. supermarket; **SM**) waste; consumer to post-consumer food waste (i.e. university residential hall dining services; **RH**), post-consumer source separated organic (**SSO**) waste (i.e. household food waste), and municipal transfer station (**TS**) waste. Specifically, these sources of food waste included the University of Minnesota Saint Paul Campus Residential Hall Dining Services (Falcon Heights, MN), the Hennepin County Recycling Center and Transfer Station (Brooklyn Park, MN), Lunds and Byerlys supermarket (Roseville, MN), and the Hennepin County Organics Recycling Program for Residents (Minneapolis, MN). The RH source provides meals to over 500 students and the food waste generated at this site is routinely collected and delivered to commercial facilities for composting. The TS source is a city waste collection and transfer station that is the only facility in the area that accepts organic waste from households and businesses, and includes a wide range of organic materials (food scraps, non-food organics such as non-recyclable paper and biodegradable products) for subsequent composting. The SM source represents a major grocery chain with 37 different stores that sell a variety of food products including bakery, dairy, meat, fruits and vegetables, and restaurant prepared foods. Finally, the SSO source is a voluntary organic recycling program conducted by the county government and provides both curbside pickup and multiple drop-off locations for residents within Hennepin County. Materials being recycled include food scraps and non-food organics including food-soiled paper products and other compostable items (e.g. yard waste).

Food Waste Sample Collection

Retail to consumer level - Supermarket

Food waste samples generated from 5 departments of the store and the in-store restaurant, were collected daily by employees and stored in multiple 120 L recycling bins separated and identified by their respective origins (e.g. dairy, fruits and vegetables, meat, bakery, and restaurant). Subsamples of food waste from each department were obtained directly from the recycling bins using a 8.1 cm × 10.4 cm × 34.5 cm plastic ladle. Each sampling location within the bins was selected randomly regardless of the materials in the bin, and samples collected were placed in a 34.3 cm × 24.4 cm × 7 cm aluminum pan for subsequent drying. Each pan was filled with 2 full scoops (approximately 400 mL) of each type of food waste, and 10 pans were filled at each collection time from 5 different bins including 1 fruit and vegetable bin, 2 meat bins (chicken and beef), 1 bakery product bin, and 1 bin from the restaurant. A total of 30 samples were collected from 3 visits in April, 2015.

Consumer to post-consumer level – University residence hall

Food waste was collected by the dining service employees on a daily basis, stored in 120 L recycling bins, and consisted of discarded food from all 3 meals from the previous day. Subsampling was done by using an 8.1 cm x 10.4 cm x 34.5 cm plastic ladle to remove two full scoops (about 400 mL) of food waste directly from recycle bins. Sampling location within the bins was selected randomly regardless of materials in the bin, and the samples were then placed in 34.3 cm × 24.4 cm × 7 cm aluminum pans for later drying. Each pan was filled with 2 full scoops (approximately 400 mL) of food waste, and 5 to 10 pans were collected at each sampling time depending on the total volume of the food waste stored in the bins at the time of collection. This resulted in a total of 6 collections over a 3-month period from February, 2015 to April, 2015.

Consumer to post-consumer level – Household Source Separated Organic Waste Recycling Program

Three of 7 drop-off SSO locations in the program were randomly selected for collection, which included Audubon Park, Pearl Park, and Armatage Park (Minneapolis, MN). Organic waste generated from households in these communities was collected by residents in program-specific recycling bags (Biodegradable Products Institute, NY) and delivered to these 3 locations. Samples were directly collected from individual drop-off containers with 1 bag/container (12 L/ bag). A total of 48 samples were collected over 2-week periods, which involved 6 visits at two different times (August, 2015 and January, 2016). Samples collected on the same day from each location were pooled to form one representative sample from each location and day of collection.

Post-consumer to municipal organic waste level - Organic waste transfer station

Organic waste at the TS was piled in a 4 m × 4 m bunker to be later transferred by trucks to a composting facility. Samples were collected by dividing the area into 9 quadrants in which 1 quadrant was approximately 1.7 m^2, and organic waste from each quadrant was subsampled using a shovel. Samples from each quadrant were randomly selected and placed into two 34.3 cm × 24.4 cm × 7 cm aluminum pans. Nine pans of waste (approximately 400 mL/pan) were collected during each of 3 visits over a 2-month period from February 2015 to March 2015.

Processing of samples

After each collection, samples in trays were weighed using a Tanita® 144 laboratory scale (Arlington Heights, IL), and weights were recorded after subtracting the aluminum tray weight from the total weight. Next, samples were dried in a forced-air oven at 60 °C for 72 h. After the 72-h period, samples were removed from the oven and weighed using the same scale to determine the dry weight of each sample. Subsequently, each tray of samples was ground and mixed individually using a robot coupe® Blixer® 3 Series D 3 ½ Qt (Ridgeland, MS) into a fine power. One hundred grams of powder was subsampled from each collection tray and sent to a commercial laboratory for chemical analysis.

Chemical analysis

All samples were submitted to Minnesota Valley Testing Laboratory (New Ulm, MN) for proximate analysis. Chemical analysis was conducted using AOAC (2006) methods for crude protein (CP; Method 990.03), ether extract (**EE**; Method 920.39), ash (Method 942.05), calcium (Method 985.01), phosphorus (Method 985.01), sodium (Method 985.01), neutral detergent fiber (**NDF**; Method 2002.04), and acid detergent fiber (**ADF**; Method 973.18). Starch was measured using an enzymatic extraction and glucose measurement method that was developed by Minnesota Valley Testing Laboratories. Gross energy (**GE**) was determined by using an adiabatic oxygen bomb calorimeter (Parr Instrument Co., Moline, IL). Samples were also submitted to University of Missouri Experiment Station Chemical Laboratories (Columbia, MO) for analysis using AOAC (2006) procedures for fatty acid profile (Method 996.06), amino acid profile (Method 982.30), peroxide value (**PV**) (Method 965.33). Thiobarbituric acid reactive substances (**TBARS**) content was determined according to the current protocols in Analytic Chemistry (2001; D2. 4.1 - D2.4.18).

Energy and iodine value calculations

Energy calculations

Three published equations from the "Nutrients Requirements of Swine" (NRC, 2012) were used to estimate the digestible energy (**DE**), metabolizable energy (**ME**), and net energy (**NE**) content of the food waste from chemical composition using analyzed chemical composition:

DE, kcal/kg DM = 1,161 + (0.749 × GE, kcal/kg DM) - (4.3 × Ash, g/kg DM) - (4.1 × NDF, g/kg DM) (Noblet and Perez, 1993)

ME, kcal/kg DM = 4,194 - (9.2 × Ash, g/kg DM) + (1.0 × CP, g/kg DM) + (4.1 × EE, g/kg DM) - (3.5 × NDF, g/kg DM) (Noblet and Perez, 1993)

NE, kcal/kg DM = (0.726 × ME, kcal/kg DM) + (1.33 × EE, g/kg DM) + (0.39 × Starch, g/kg DM) - (0.62 × CP, g/kg DM) - (0.83 × ADF, g/kg DM) (Noblet et al., 1994)

Iodine value calculations

Iodine value (**IV**) equations from NRC (2012) were used to calculate both total IV and iodine value of product (**IVP**) based on the fatty acid profiles of the food waste samples:

Total IV = (C16:1 × 0.9976) + (C18:1 × 0.8985) + (C18:2 × 1.8099) + (C18:3 × 2.7345) + (C20:1 × 0.8173) + (C20:4 × 3.3343) + (C20:5 × 4.1956) + (C22:1 × 0.7496) + (C22:5 × 3.8395) + (C22:6 × 4.6358)

and

IVP = (IV of ingredient EE) × (% EE in the ingredient) × 0.1

Statistical analysis

Individual samples from each location and collection tray was considered as the experimental unit for all analyses. Chemical composition data, calculated energy and iodine values, and lipid peroxidation data were analyzed using the GLM procedure of SAS 9.3 (SAS Inst. Inc., Cary, NC). Food waste source was considered as a fixed effect. Data were analyzed using a general linear model that included food waste source as the main factor, and least squared means with adjustment were used for multiple comparisons. Significant differences were designated if $P \leq 0.05$ and trends were noted when $0.05 < P < 0.10$.

RESULTS AND DISCUSSION

Analyzed chemical composition and calculated energy values of food waste sources

All analyzed nutrient values are expressed on a DM basis. No differences were observed in the moisture content among food waste sources during the initial drying process (60 °C for 72 h), and subsequent DM analysis after the initial drying. However, the initial moisture content of all the food waste sources was greater than 60% (Table 5). Because dry feeding systems are the predominant form used in the U.S. pork industry (Richert and DeRouchey, 2010), the high moisture content of all sources of food waste requires drying before they can be incorporated into diets in commercial feed mills used in pork production systems. The initial drying process of 60 °C for 72 h was effective in reducing the moisture content to 5 to 10%, which is common for feed ingredients such as corn (11.7%) and soybean meal (4.4%). High moisture content in food waste can increase the susceptibility to microbial growth and spoilage, and as a result, requires thermal heating to remove moisture before it can be fed to swine (Kabak et al., 2006).

Supermarket food waste had the greatest concentration of CP (25.5%) and EE (31.6%) compared with all the other sources ($P < 0.05$). The relatively high concentration of CP and EE in the SM samples was a result of the high proportion of meat products in the collected waste. There were no differences in CP and EE content among RH (18.90%

CP, 13.58% EE), TS (17.71% CP, 11.09% EE) and SSO (13.53% CP, 10.60% EE) sources. The relatively high CP and EE content of these food waste sources suggest that they may be valuable feed ingredients in swine diets because energy provided by EE and protein are the two most expensive nutritional components (Kerr et al., 2015; Zhou et al., 2015). When comparing the CP and EE content in the food waste sources with that in corn and soybean meal, CP content (26 to 14%) was intermediate between corn (9.3%) and dehulled, solvent extracted soybean meal (47.2%), while EE content in food waste (31.6 to 10.6%) exceeded that in corn (3.9%) and soybean meal (1.7%).

The fiber content of TS (23.0% NDF, 19.8% ADF) and SSO (24.6% NDF, 17.4% ADF) was greater ($P < 0.05$) for SM (12.4% NDF, 12.9% ADF) and RH (6.7% NDF, 5.3% ADF) samples. The high proportion of fiber in both TS and SSO samples was expected because these food waste sources were comprised primarily of fruit and vegetable waste. Vegetables and fruit waste contain a significant amount fiber on a DM basis, and as a result, would be expected to reduce ME and NE content of these food waste sources for swine. The inclusion of high fiber ingredients in swine diets has been shown to reduce energy and nutrient digestibility, increaseg digesta passage rate, and reduce efficiency of growth (Kennelly and Aherne, 1980; Kerr et al., 2013; Myrie et al., 2008; Pérez de Nanclares et al., 2017). However, mechanical processing (e.g. pelleting and micronizing), and the addition of exogenous enzymes have been shown to increase the utilization of non-starch polysaccharides in some high fiber ingredients (Kerr et al., 2013).

Starch content was greater ($P < 0.05$) in the RH samples (42.1%) compared with SM (11.6%), TS (16.3%) and SSO (12.5%) sources, and the relatively high starch content in the RH samples was likely due to the high proportion of bakery goods and pizza waste. Starch is a highly digestible energy source in animal feed (Keys and DeBarthe, 1974; Noblet, 2000), and provides high energy and economic value in swine diets.

Supermarket (7.7%) and TS (7.7%) samples had a greater ($P < 0.05$) concentration of ash compared with RH (5.0%) and SSO (5.6%) samples. Calcium content was greater ($P < 0.05$) in SM (0.98%), TS (1.02%) and SSO (0.85%) samples compared with RH samples (0.25%). However, sodium content was greater ($P < 0.05$) in the SM (0.77%), RH (0.85%) and TS (0.72%) samples compared to SSO (0.29%) samples. However, there were no differences in phosphorus content among these 4 food waste sources. The relatively high phosphorus and calcium content in the SM waste was likely a result of the high proportion of meat, dairy and processed deli products in this food waste mixture. Yet, the concentrations of phosphorus and calcium in all of these food waste sources (< 1%) are not great enough to be considered as major sources of these minerals in swine diets.

Energy is the most expensive nutritional component in swine diets. Therefore, it is very important to estimate the ME or NE content of feed ingredients before feed formulation (Kerr et al., 2015). The analyzed GE content was greater ($P < 0.05$) for the SM samples (5,909 kcal/kg) and RH samples (5,419 kcal/kg) compared with TS (4,829 kcal/kg) and SSO (4,455 kcal/kg) samples. Food waste from SM had greater ($P < 0.05$) calculated DE (5,016 kcal/kg), ME (4,832 kcal/kg), and NE (3740 kcal/kg) compared with the other food waste sources, while TS samples had the least ($P < 0.05$) DE (3,421 kcal/kg), ME (3,198 kcal/kg), and NE (2,252kcal/kg). The DE, ME and NE content of RH and SSO samples were similar despite the differences in GE content. When compared to corn (3,933 kcal/kg GE, 3,451 kcal/kg DE 3,395 kcal/kg ME 2,672 kcal/kg NE), which is the major energy contributor in U.S. swine diets, SM, RH and SSO samples had greater GE, calculated DE, ME and NE content, while TS samples had less estimated DE, ME and NE content than corn due to its high concentration of NDF. Thus, adding food waste sources from SM, RH, and SSO to swine diets would provide greater ME and NE than corn. However, the accuracy of the energy prediction equations used in this study have not been validated for use in food waste sources. Therefore, the DE, ME, and NE content of food waste sources should be determined experimentally to verify the accuracy of their energy content before feeding them to swine (Kil et al., 2013).

Amino acid profile of food waste sources

Considering that Lys, Met, Thr, and Trp) are the first 4 limiting amino acids in corn-soybean meal-based diets for swine, SM food waste samples had the greatest ($P < 0.05$) concentration of all these amino acids (1.82% Lys, 0.27% Trp, 1.07% Thr and 0.53% Met) compared with the other 3 food waste sources (Table 6). However, there were no differences in Lys, Met, Thr content among RH, TS and SSO sources, but TS and SSO had less ($P < 0.05$) Trp content (0.13% and 0.08%, respectively) compared with samples of SM (0.27%) and RH (0.20%). Amino acid content, digestibility, and their proportions relative to the first limiting are important factors when formulating diets to optimize growth performance and lean tissue protein accretion in pigs (Fuller, 1989; Kerr and Easter, 1995; Stein et al., 2007). The Lys, Trp, Thr and Met content in all food waste sources was greater than corn (0.28% Lys, 0.07% Trp, 0.32% Thr and 0.20% Met), but less than soybean meal (3.29% Lys, 0.73% Trp, 2.07% Thr and 0.73% Met). Swine diets should be formulated on a standardized ileal digestible amino acid basis rather than total amino acid basis to accurately supply amino acids without excess or deficiencies (Sauer and Ozimek, 1986). Because of differences in chemical characteristics, and the extent of previous processing and heating of the food waste sources evaluated in this study, the digestibility of amino acids is uncertain (Sauer et al., 1991; Stein et al., 2007). Therefore, direct in vivo determination of the digestibility of amino acids is necessary before formulating diets containing these food waste sources (Stein et al., 2007).

Although the concentration of biogenic amines was not determined in food waste sources evaluated in this study, the concentrations of putrescine, cadaverine, spermidine, spermine should also be determined before adding to swine diets. Biogenic amines are resulting products of the decarboxylation of free amino acids by bacteria found in animal tissues and plants (Salazar et al., 2000; Brink et al., 1990). High concentrations of biogenic amines may indicate significant spoilage and degradation of high protein feed ingredients, and feeding diets containing high concentrations of these compounds can result in toxicity and reduction of growth performance in animals (Salazar et al., 2000; Smith, 1990; Teti et al., 2002).

Fatty acid profile and lipid quality of food waste sources

The concentration of linoleic acid (C18:2) was greater ($P < 0.05$) in the TS samples (32.8%) compared to SM (15.9%) and SSO (23.3%) sources. However, the concentration of linoleic acid in RH samples (29.3%) was not different from the 3 other food waste sources. Linolenic acid (C18:3) content was also greater ($P < 0.05$) in the TS samples (7.1%) compared with the other 3 sources, but there were no differences in the linolenic acid content among samples of SM (2.2%), RH (3.8%), and SSO (2.4%). Finally, the concentration of arachidonic acid was not different among samples of SM (0.23%), RH (0.20%) and TS (0.24%) food waste. The SSO samples had less ($P < 0.05$) arachidonic acid content compared with TS samples, but arachidonic acid content was not different from SM and RH samples. The concentration of fatty acids and their relative proportions are important in feeding programs because they supply essential fatty acids such as linoleic and linolenic acid (NRC, 2012). However, feeding high amounts of polyunsaturated fatty acids have been shown to reduce pork fat firmness (Villela et al., 2017; Wu et al., 2016). Thus, it is important to determine the fatty acid composition of lipids in various feed ingredients when formulating growing-finishing pig diets to achieve acceptable pork fat quality. It is difficult to achieve the desired balance fatty acids in diets because there are multiple fatty acids present in various concentrations among feed ingredients. Therefore, Iodine Value Product (**IVP**) and other carcass fat quality predictions have been developed to simplify diet formulation. For example, the IV of distillers' corn oil, soybean oil, and palm (vegetable derived oils widely available for feeding swine around the world) is relatively high compared with that of palm oil (Lindblom et al., 2017). Also, choice white grease and tallow are commonly used animal fat sources in swine diets, and have an IVP less than distillers corn oil (Davis et al., 2015). Relative to these common supplemental lipid sources, food waste has a concentration of polyunsaturated fatty acids that is comparable to corn oil. However, the fatty acid composition in various food waste sources is dependent on the origin of the fats and oils present in specific food waste sources.

Because of the relatively high EE content in food waste, exposure to high cooking and thermal processing conditions during drying, lipid peroxidation may occur. Therefore, PV and TBARS were evaluated using lipids extracted from these food waste sources. Peroxide value was greater ($P < 0.05$) in SSO samples (82.43 meq/kg oil) compared with the other 3 sources, but there were no differences between SM (66.44 meq/kg oil), RH (62.33 meq/kg oil) or TS (62.16 meq/kg oil) samples. The same pattern was also observed for TBARS values, where SSO samples (2.44 mg MDA eq/g oil) had greater ($P < 0.05$) TBARS values compared with the 3 other sources, but there were no differences between SM (0.17 mg MDA eq/g oil) RH (0.16 mg MDA eq/g oil) and TS (0.18 mg MDA eq/g oil) sources. A relatively high concentration of TBARS was observed in SSO waste, which was likely due to high temperatures used during cooking in the households, as well as the extended storage time at collection sites with thermal and oxygen exposure, before the sampling took place.

Feeding peroxidized lipids to pigs has been shown to reduce growth performance, impair immune function, and reduce pork quality ((Takahashi and Akiba, 1999; Wood et al., 2004; Kerr et al., 2015; Hanson, 2014; Hung et al., 2017). In addition, high concentrations of TBARS in the feed can lead to detectable off flavors in the meat, with the range of 0.5 – 1.0 mg MDA/kg in final meat products (Greene and Cumuze, 1982). However, addition of antioxidants to feed ingredients and complete feeds containing high lipid content may mitigate the adverse effect of feeding peroxided lipid to the animals, even though antioxidants added to feed does not reverse the state of peroxidation (Kerr et al., 2015; Sherwin and Products, 1978). Thus, it is important to minimize exposure to high heat and oxygen when processing the food waste into animal feed, as well as the length of time it is stored before collection and processing. The maximum diet inclusion rate of food waste in swine diets will be influenced by the lipid content, fatty acid profile, and extent of peroxidation in food waste sources.

In conclusion, food waste collected from a supermarket, University residence dining hall, transfer station, and household source separated organic sources varied in chemical composition due to the types of food waste and the segment of the food supply chain where they were collected. These results support our hypothesis that food waste from up-steam sources (i.e. supermarket and residence hall dining hall) are less diluted with other non-food organics (i.e. transfer station and household source separated organics) and have greater feeding value in swine diets than downstream sources. However, significant variability was observed within each source of food waste, which may require blending of multiple batches within source to provide more consistency in nutrient content to the feed industry. The concentrations of biogenic amines and peroxidized lipids should be considered when evaluating the use and nutritional value of various food waste sources in swine diets. Although food waste sources evaluated in this study appear to be suitable sources of energy and nutrients for commercial swine diets, further research is needed to directly determine ME and NE content, as well as amino acid and phosphorus digestibility when using these food waste sources in precision swine feeding programs.

Table 5. Analyzed nutrient composition and calculated energy content (DM basis) of food waste from pre-consumer (supermarket), post-consumer University Dining Hall and household source separated organics), and municipal organic waste collection (transfer station) facilities in Minnesota compared with nutritional composition of corn and dehulled, solvent extracted soybean meal (NRC, 2012)

	Supermarket (n = 22)		**University Dining Hall (n = 60)**		**Transfer Station (n = 27)**		**Source Separated Organics (n=12)**			**Soybean Meal[1]**		**Corn[2]**	
Item	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**SEM**	**Mean**	**SD**	**Mean**	**SD**
Moisture 1[3], %	61.08	17.16	60.85	12.03	69.07	10.44	72.52	10.30	2.42	NA[5]	NA	NA	NA
Moisture 2[4], %	8.33	12.49	7.02	4.76	9.84	6.22	5.15	0.69	1.46	10.02	2.62	11.69	2.41
Crude protein, %	25.51^{a}	13.50	18.90^{b}	3.15	17.71^{b}	6.86	13.53^{b}	3.73	1.49	53.05	2.30	9.33	0.93
Ether extract, %	31.57^{a}	18.96	13.58^{b}	3.37	11.09^{b}	6.35	10.60^{b}	5.51	2.05	1.69	0.91	3.94	0.78
Ash, %	7.73^{a}	4.59	5.01^{b}	1.27	7.73^{a}	3.60	5.58^{ab}	2.22	0.55	7.47	0.51	1.47	0.32
Ca, %	0.98^{a}	1.04	0.25^{b}	0.21	1.02^{a}	0.94	0.85^{a}	0.89	0.14	0.37	0.10	0.02	0.01
P, %	0.64	0.60	0.30	0.07	0.46	0.36	0.31	0.16	0.11	0.79	0.09	0.29	0.05
Na, %	0.77^{a}	0.38	0.85^{a}	0.17	0.72^{a}	0.87	0.29^{b}	0.10	0.08	0.09	0.05	0.02	0.00
NDF[6], %	12.37^{b}	8.05	6.72^{b}	9.14	22.99^{a}	12.53	24.59^{a}	6.80	2.16	9.12	2.90	10.32	1.97
ADF[7], %	12.92^{b}	8.27	5.29^{c}	6.88	19.76^{a}	10.45	17.44^{ab}	4.87	1.69	5.87	2.43	3.26	0.83

Starch, %	11.57[b]	13.45	42.11	10.57	16.28[b]	9.62	12.50[b]	5.53	2.36	2.10	NA	70.83	4.61
Energy (kcal/kg)													
GE[8]	5,909[a]	1,016	5,419[a]	349	4,829[b]	486	4,455[b]	309	140	4,730	192	3,933	86
DE[9]	5,016[a]	1,152	4,418[b]	425	3,421[c]	721	4,552[b]	283	120	4,022	184	3,451	111
ME[10]	4,832[a]	1,274	4,188[b]	422	3,198[c]	575	4,114[b]	44	120	3,660	NA	3,395	NA
NE[11]	3,740[a]	1,188	3,221[b]	407	2,252[c]	532	2,983[b]	40	110	2,319	NA	2,672	NA

[a,b,c] Means with different superscripts within a row differ ($P < 0.05$)

[1]Soybean meal, dehulled solvent extracted mean and standard deviation values were obtained from NRC (2012)

[2]Yellow dent corn mean and standard deviation values were obtained from NRC (2012)

[3]Moisture content after initial drying process at 60°C for 72 hours.

[4]Moisture content of initially dried samples at 135°C for 2 hours.

[5]NA = not applicable

[6]NDF = Neutral detergent fiber

[7]ADF = Acid detergent fiber

[8] GE = Gross energy (kcal/kg) determined by adiabatic bomb calorimetry

[9] DE = Calculated digestible energy (kcal/kg) = 1,161 + (0.749 × GE, kcal/kg) - (4.3 × Ash, g/kg) - (4.1 × NDF, g/kg) (Noblet and Perez 1993)

[10]ME = Calculated metabolizable energy (kcal/kg) = 4,194 - (9.2 × Ash, g/kg) + (1.0 × CP, g/kg) + (4.1 × Ether extract, g/kg) - (3.5 × NDF, g/kg) (Noblet and Perez 1993)

[11]NE = Calculated net Energy (kcal/kg) = (0.726 × ME, kcal/kg) + (1.33 × Ether extract, g/kg) + (0.39 × Starch, g/kg) - (0.62 × CP, g/kg) - (0.83 × ADF, g/kg) (Noblet et al. 1994)

Table 6. Indispensable amino acid content (DM basis) of food waste from pre-consumer (supermarket), post-consumer (University Dining Hall and household source separated organics), and municipal organic waste collection (transfer station) facilities in Minnesota compared with corn and dehulled, solvent extracted soybean meal (NRC, 2012)

	Supermarket (n=17)		University Dining Hall (n=55)		Transfer Station (n=22)		Source Separated Organics (n= 12)			Soybean Meal[1]		Corn[2]	
Amino acid, %	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**SEM**	**Mean**	**SD**	**Mean**	**SD**
Arginine	1.63^{a}	1.09	0.79^{b}	0.19	0.59^{b}	0.27	0.58^{b}	0.20	0.10	3.83	0.26	0.42	0.05
Histidine	0.72^{a}	0.42	0.44^{b}	0.12	0.29^{c}	0.14	0.33^{bc}	0.09	0.04	1.42	0.10	0.27	0.05
Isoleucine	1.08^{a}	0.56	0.72^{b}	0.16	0.54^{b}	0.24	0.52^{b}	0.13	0.06	2.38	0.18	0.32	0.06
Leucine	1.96^{a}	1.03	1.27^{b}	0.29	0.96^{b}	0.41	0.94^{b}	0.22	0.11	4.02	0.27	1.09	0.15
Lysine	1.82^{a}	1.27	0.77^{b}	0.32	0.67^{b}	0.31	0.63^{b}	0.22	0.13	3.29	0.19	0.28	0.04
Methionine	0.53^{a}	0.34	0.31^{b}	0.08	0.22^{b}	0.12	0.22^{b}	0.07	0.04	0.73	0.08	0.20	0.03
Phenylalanine	1.06^{a}	0.51	0.80^{b}	0.16	0.58^{c}	0.24	0.57^{c}	0.12	0.06	2.67	0.19	0.44	0.05
Threonine	1.07^{a}	0.62	0.59^{b}	0.14	0.47^{b}	0.20	0.43^{b}	0.12	0.06	2.07	0.11	0.32	0.04
Tryptophan	0.27^{a}	0.14	0.20^{b}	0.05	0.13^{c}	0.06	0.08^{c}	0.03	0.02	0.73	0.08	0.07	0.01
Valine	1.23^{a}	0.63	0.79^{b}	0.18	0.59^{b}	0.26	0.66^{b}	0.14	0.07	2.48	0.19	0.43	0.05

[a,b,c] Means with different superscripts within a row differ ($P < 0.05$)
[1]Soybean meal, dehulled solvent extracted mean and standard deviation values were obtained from NRC (2012)
[2]Yellow dent corn mean and standard deviation values were obtained from NRC (2012)

Table 7. Fatty acid composition (% of ether extract), lipid peroxidation indicators, iodine value (IV), and iodine value product (IVP) of food waste (DM basis) from pre-consumer (supermarket), post-consumer (University Dining Hall and household source separated organics), and municipal organic waste collection (transfer station) facilities in Minnesota compared with corn and dehulled, solvent extracted soybean meal (NRC, 2012)

	Supermarket (n=17)		**University Dining Hall (n=55)**		**Transfer Station (n=22)**		**Source Separated Organics (n= 12)**			**Soybean Meal[1]**		**Corn[2]**	
Measurement	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**SEM**	**Mean**	**SD**	**Mean**	**SD**
Ether extract, %	31.57[a]	18.96	13.58[b]	3.37	11.09[b]	6.35	10.60[b]	5.51	2.05	1.52	0.91	3.94	0.78
Linoleic acid (18:2n6), %	15.88[b]	9.38	29.31[ab]	5.48	32.76[a]	11.74	23.34[b]	6.36	1.75	49.17	NA[3]	44.24	NA
Linolenic acid (18:3n3), %	2.19[b]	2.47	3.82[b]	1.12	7.05[a]	6.27	2.43[b]	0.75	0.69	1.52	NA	1.37	NA
Arachidonic acid (20:4n6), %	0.23[ab]	0.12	0.20[ab]	0.11	0.24[a]	0.18	0.13[b]	0.10	0.03	0.00	NA	NA	NA
Lipid peroxidation													
Peroxide value, meq/kg lipid	66.44[b]	18.17	62.33[b]	15.00	62.16[b]	18.38	82.43[a]	50.88	4.88	NA	NA	NA	NA
TBARS[4], mg MDA eq/g lipid	0.17[b]	0.05	0.16[b]	0.05	0.18[b]	0.05	2.44[a]	1.55	0.11	NA	NA	NA	NA
Lipid composition													
IV[5]	68.15[c]	17.06	86.60[ab]	9.53	90.60[a]	16.29	78.63[b]	9.01	2.77	NA	NA	NA	NA
IVP[6]	211.29[a]	81.02	95.22[b]	25.35	77.84[b]	46.02	71.42[b]	39.34	9.88	NA	NA	NA	NA

[a,b,c] Means with different superscripts within a row differ ($P < 0.05$)
[1]Soybean meal, dehulled solvent extracted mean and standard deviation values were obtained from NRC (2012)
[2]Yellow dent corn mean and standard deviation values were obtained from NRC (2012)
[3]NA = not applicable
[4]Thiobarbituric acid reactive substances
[5]IV = calculated iodine value of extracted lipid = (C16:1 × 0.9976) + (C18:1 × 0.8985) + (C18:2 × 1.8099) + (C18:3 × 2.7345) + (C20:1 × 0.8173) + (C20:4 × 3.3343) + (C20:5 × 4.1956) + (C22:1 × 0.7496) + (C22:5 × 3.8395) + (C22:6 × 4.6358) (NRC, 2012)
[6]IVP = calculated IV product of extracted lipid = (IV of ingredient ether extract) × (% of ether extract in the ingredient) × (0.1) (NRC, 2012)

Chapter 3

Energy, amino acid, and phosphorus digestibility and energy prediction of thermally treated food waste sources for swine

Published at:

Fung, L., P. E. Urriola, and G. C. Shurson. (2019). Energy, amino acid, and phosphorus digestibility and energy prediction of thermally processed food waste sources for swine. Translational Animal Science, 3(2), 676–691. https://doi.org/10.1093/tas/txz028

Abstract

Recycling energy and nutrients from food waste into animal feed decreases the environmental impact of food animal production. However, recycling energy and nutrients from various food waste sources into swine feeding programs is constrained by the high variability and lack of data on the digestibility of energy and nutrients. Therefore, the objectives of this study were to evaluate the digestibility of energy, amino acids, and phosphorus in thermally-dried food waste sources fed to growing pigs, and to compare in vivo determined digestibility values with those obtained from in vitro digestibility procedures and published prediction equations to determine the accuracy of using these nutritional evaluation methods. Pigs (n = 36; initial body weight = 16.37 ± 1.9 kg) were utilized to determine digestible energy (DE) and metabolizable energy (ME) content, as well as standardized total tract digestibility (STTD) of phosphorus and standardized ileal digestibility (SID) of amino acids in 3 sources of dehydrated food waste in 3 separate trials. Initial body weight of pigs at the beginning of each digestibility trial was used as the blocking factor in a randomized complete block design. Diets were formulated to contain 30% food waste derived from fish waste (FW), supermarket waste (containing bakery, fruits and vegetables, meat, and deli foods from a single supermarket; SMW), and fruit and vegetable waste (FVW). The DE and ME content of FW (DE = 5,057 kcal/kg; ME = 4,820 kcal/kg) and SMW (DE = 5,071 kcal/kg; ME = 4,922 kcal/kg) were not different ($P > 0.05$), while FVW had the least ($P < 0.05$) DE (2,570 kcal/kg) and ME (2,460 kcal/kg) content compared with FW and SMW. Digestibility of crude protein and amino acids were greater ($P < 0.05$) in FW and SMW compared with FVW. The in vitro digestibility procedure can be used to approximate the digestibility of DM and energy in SMW, FW and FVW compared with in vivo estimates, but significant error exists depending on the chemical characteristics of each food waste source. However, use of the prediction equations and digestibility data obtained from the in vitro procedure resulted in high accuracy in estimating DE content of FW (observed = 5,058 kcal/kg DM vs. predicted = 4,948 kcal/kg DM), SMW (observed = 5,071 kcal/kg DM vs. predicted 4,978 kcal/kg DM) and FVW (observed = 2,570 kcal/kg DM vs. predicted 2,814 kcal/kg DM) sources.

1. INTRODUCTION

In the United States, food waste accounts for 21.6 % of the discarded municipal solid waste, and only 5% of food waste generated is diverted away from landfills annually (U.S. EPA, 2014). As a result, there is increasing interest in utilizing food waste as animal feed because of its environmental benefits, low cost, and diversion from low value landfill disposal to higher value animal feed products (Esteban et al., 2007; Salemdeeb et al., 2017).

Feed cost accounts for about 65 to 75% of the total cost of pork production (Thaler and Dakota, 2010). Increased use and prices of grain and lipids in biofuel production have contributed to increased interest in using lower cost alternative feed ingredients in commercial swine diets (Woyengo et al., 2014). In the United States, most commercial pork production systems use dry feeding rather than liquid feeding systems, and diets are based on grains, soybean meal, and various by-products (e.g. distillers dried grains with solubles, wheat middlings, bakery waste (Richert and DeRouchey, 2010). Limited studies have evaluated the nutritional value of feeding wet (Jinno et al., 2018) or dried post-consumer food waste to growing pigs (Westendorf et al., 1998; Myer et al., 1999). However, results from these previous studies suggest that inclusion of dried food waste in practical swine diets had little to no effect on growth performance and carcass composition of pigs compared with feeding standard corn-soybean based diets (Westendorf et al., 1998). However, these studies evaluated only one food waste source, which was not representative of the wide variety of food waste sources produced in various segments of the food chain. Therefore, more food waste sources with varying nutritional characteristics need to be evaluated for their potential use in swine feeding programs.

To meet the daily energy and digestible nutrient requirements of pigs, information on the digestible (**DE**) and metabolizable energy (**ME**) content, standardized ileal digestibility (**SID**) of amino acids, and standardized total tract digestibility (**STTD**) of phosphorus is needed for all feed ingredients being fed (NRC, 2012). There are no published *in vivo* data for DE, ME, SID of amino acids (**AA**), or STTD of phosphorus for various food waste sources. Likewise, there are no data on the accuracy of estimating DE, ME, SID of amino acids, or STTD of phosphorus using *in vitro* assays, or predicting DE and ME content from published equations. Therefore, the objective of the study was to determine the concentration of DE and ME, as well as SID of AA and STTD of phosphorus of 3 sources of thermally-processed food waste, and to compare *in vivo* determined values with those derived from *in vitro* digestibility determinations as well as prediction equations based on chemical composition of the food waste sources for swine.

2. MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Minnesota reviewed and approved protocol #1601-34068A for these experiments.

2.1 Dehydrated food waste sources and chemical analysis

Three dehydrated food waste sources (fish waste **FW**; supermarket waste **SMW**; fruit and vegetable waste **FVW**) were collected and processed by TUBS, Inc. (Minneapolis, MN) for use in this study. The FW was obtained from a single fish processing facility in Minnesota, and the FVW was collected from a local fruit and vegetable processing plant. The SMW was composed of a mixture of fruits and vegetables, deli foods, meat, and bakery products from a local supermarket. Three composite samples were collected at the supermarket over a 3-week period, and each collection consisted of waste collected over a 2-day period from the 4 departments and stored in 120 L barrel. Thus, the final product was a mixture of food waste representing a total of 6 days from the four departments. After collecting the raw materials from their respective sources, the 3 food waste sources were ground and mixed individually through an auger screw press and dehydrated using a drum dryer to achieve a final moisture content of less than 80%. Samples were then stored in 20 L buckets at -4°C before submitting for chemical analysis.

The 3 dehydrated sources of food waste were subsampled and submitted to the University of Missouri Agricultural Experiment Station Chemical Laboratories (Columbia, MO) for chemical analyses (Table 8). Samples were analyzed using AOAC (2012) procedures for AA profile (Method 982.30), acid detergent fiber (**ADF**; Method 973.18), crude protein (**CP**; Method 984.13), ether extract (**EE**; Method 920.39), ash (Method 942.05), dry matter (**DM**; Method 934.01), phosphorus (Method 966.01), calcium (Ca; Method 980.02). Neutral detergent fiber (**NDF)** was analyzed as described by Van Soest (1991), and thiobarbituric reactive substances (**TBARS**) as described by Wrolstad (2001). Thiobarbituric reactive substances were measured in all food waste samples because of the potential for lipid peroxidation before processing, as well as during the heating and dehydration processes. The *in vivo* determinations of DE, ME, SID AA, and STTD P were conducted in 3 separate experiments, and the same batch of each source of food waste was used in all experiments. Pigs were weighed between experiments to calculate the daily feed allowance based on initial body weight (**BW**).

2.1 Energy balance and concentration of DE and ME

2.1.1 Diets, animals, and experimental design

The first experiment was designed to determine the DE and ME content in FW, FVW and SMW. Thirty-six growing barrows (initial BW = 16.37 ± 1.9 kg) were housed individually in metabolism crates equipped with a stainless-steel feeder and nipple waterer, using a randomized complete block design with initial BW as the blocking factor. Pigs within block were assigned randomly to 1 of 4 dietary treatments consisting of a basal control diet containing 96.9% corn and 3 test diets consisting of 30% of each respective food waste source to replace corn in the basal diet (Table 9.). Titanium dioxide was added at 0.40% to each diet to serve as an indigestible marker for use in digestibility calculations. Vitamins and minerals were included in the diets to meet or exceed requirements for growing pigs based on 15 kg body weight (NRC, 2012).

2.1.2 Feeding and sample collection

Pigs were fed the experimental diets for 9 days, which included a 5-day adaptation period followed by a 4-day feces and urine collection period. Daily feed allowance was calculated according to 3 times the maintenance energy requirement of the smallest pig in each treatment (197 kcal ME/kg of body weight $^{0.60}$; NRC, 2012), and was divided and fed in two equal meals at 0800 and 1600 h. All pigs had ad libitum access to water from nipple drinkers. Representative samples of feces excreted were collected twice daily starting from 0800 h on day 6 to day 13 and stored immediately at -20^{o}C after collection until further analyses. Urine collection was initiated at 1600 h on day 5 by placing buckets under the collection pan of each metabolism crate. Urine was collected daily, and 50 mL of 3 N HCL was added to each collection container before each collection day through day 13. The total volume of urine was measured daily, and about 10% of the total volume was subsampled, filtered through glass wool, and stored at -20^{o}C until further analyses.

2.1.3 Chemical analyses

After the 4-day collection period, fecal samples were dried at 65°C in a forced-air oven for 24 h and ground through a 2-mm screen. Urine samples were thawed and mixed before subsampling for drying in a forced-air oven at 55 ˚C for 24 h (Jacobs et al., 2011). Fecal and urine samples were analyzed in duplicates for gross energy (**GE**) using an isoperibol bomb calorimeter (Parr 6400; Parr Instrument Company, Moline, IL). Diets and fecal subsamples were also submitted to the University of Missouri Agricultural Experiment Station Chemical Laboratories and analyzed for ADF, NDF,CP, EE, Ash, DM as previously described. Diets and fecal samples were also analyzed for titanium dioxide (Myers et al., 2004).

2.1.4 Calculations and statistical analysis

Digestible energy and ME content of the diets was determined by the difference method relative to the proportion of indigestible marker content (Adeola, 2001). The individual pig was considered as the experimental unit and data were analyzed using the Mixed procedure of SAS (SAS Inst. Inc., Cary, NC). Dietary treatments were fixed effects and block was considered as a random effect. Data are presented as the least squared means using the Tukey adjustment for multiple comparisons. The univariate procedure of SAS was used to search for outliers and patterns in studentized residuals. Significance was noted when $P \leq 0.05$ and trends were noted at $0.05 \leq P \leq 0.10$.

2.2 Phosphorus digestibility

2.2.1 Diets, animals, and experimental design

The objective of the second experiment was to determine the apparent total tract digestibility (**ATTD**) and standardized total tract digestibility (**STTD**) of phosphorus of the 3 food waste ingredients. The same 36 growing barrows used in the energy balance experiment (initial BW = 15.87±2.3 kg) were weighed after that experiment and continued to be individually housed in metabolism crates equipped with a stainless-steel feeder and nipple waterer. A randomized complete block design was used, which consisted of three dietary treatments providing 12 replicates per treatment. Individual BW of the pigs was used as the blocking factor. Three diets were formulated to contain 30% of the test ingredients (FW, SMW, and FVW), 49.9% corn starch and 15% sucrose (Table 10). Food waste ingredients provided the only source of P in the diets. Titanium dioxide was added at 0.40% of the diet as an indigestible marker, which was used to determine P digestibility by difference (Agudelo et al., 2010; Zhang and Adeola, 2017). Vitamins and minerals were included in the diets to meet or exceed the requirements for growing pigs based on 20 kg body weight (NRC, 2012).

2.2.2 Feeding and sample collection

Pigs were fed their assigned experimental diets for 9-d, which included a 5-d adaptation period followed by a 4-d fecal collection period. Daily feed allowance was calculated based on 3 times the maintenance energy requirement of the smallest pig in each treatment, and was equally divided into 2 equal meals that were fed at 0800 and 1600 h. All pigs had ad libitum access to water. Fecal samples were collected twice daily starting from 0800 h on d 6 and stored immediately at -20ºC after collection.

2.2.3 Chemical analyses

After completing the 4-d total collection period, fecal samples were dried at 65ºC in a forced-air oven for 24 h and ground finely to pass a 2-mm screen. Diets were analyzed for titanium, DM, ash, Ca, P, ADF, NDF and GE as previously described, and fecal samples were analyzed for titanium, DM and P.

2.2.4 Calculations and statistical analysis

The ATTD of P was calculated according to the difference method described by Agudelo et al. (2010), and the STTD was calculated by subtracting a constant basal endogenous loss of P, which was estimated to be 190 mg/kg DM intake (NRC, 2012).

Individual pig was used as the experimental unit, and data were analyzed using the Mixed procedure of SAS with Tukey adjustment for mean separation. Dietary treatments were fixed effects and block was considered as a random effect. Significance was noted when $P \leq 0.05$ and trends were noted when $0.05 \leq P \leq 0.10$.

2.3 Amino acid digestibility

2.3.1 Diets, animals and experimental design

The objective of the third experiment was to determine the apparent ileal digestibility (**AID**) and SID of AA of the 3 food waste sources. The 36 growing barrows used in the energy balance and phosphorus digestibility experiments were also used in the AA digestibility experiment. Upon the completion of the phosphorus digestibility experiment, pigs (initial BW = 21 ± 3.5 kg) were surgically fitted with a T-cannula at the distal ileum. Pigs were individually housed in metabolism crates, in a randomized complete block design (blocks were based on initial pig BW) with 4 dietary treatments to provide 9 replicates per treatment. Three corn starch-based diets contained 30% food waste from either FW, SMW or FVW as the sole source of AA, and one nitrogen-free diet to estimate the basal endogenous losses of CP and AA, were fed. Titanium dioxide was included at 0.40% of each diet as an indigestible marker for AA digestibility calculations as described in Stein et al. (2007). Vitamins and minerals were included in the diets to meet or exceed requirements for growing pigs based on 25 kg BW (NRC, 2012).

2.3.2 Feeding and sample collection

Pigs were fed their assigned experimental diets for 7 days, which included a 5-day adaptation period followed by a 2-day ileal digesta collection period. Daily feed allowance was calculated to be equivalent to 3 times the maintenance energy requirement of the pig with the lowest BW in each treatment, and was equally divided into 2 meals fed at 0800 and 1600 h. All pigs had ad libitum access to water. Ileal digesta were collected for 8 h on day 6 and 7, beginning at 0800 h and continuing until 1600 h. A 207 mL bag (Whirl-pack, Nasco Fort Atkinson, WI) was attached to the barrel of the cannula using a cable zip-tie during total collection of ileal digesta samples. Bags were replaced whenever they were filled or at 30 min intervals. All samples were stored at -20^{o}C before analysis.

2.3.3 Chemical analyses

After the 2-day collection, digesta samples were thawed, mixed and subsampled before lyophilization for 5-day, and dried samples were subsequently ground to pass a 2-mm screen. Diets were analyzed for AA profile, titanium, DM, ash, ADF, NDF and GE content as previously described, and digesta samples were analyzed for AA profile, DM, and titanium concentrations.

2.3.4 Calculations and statistical analysis

Endogenous losses of CP and AA, as well as AID and SID of the food waste ingredients were calculated as described by Stein et al. (2007) using an indigestible marker. Individual pig was used as the experimental unit and data were analyzed by the Mixed procedure of SAS using model and analysis described for experiment 1.

2.4 *In vitro* DM and energy digestibility of FW, SMW, FVW and corn

Samples of FW, SMW, FVW, and corn were analyzed using a 3-step *in vitro* enzymatic hydrolysis and fermentation procedure to determine the *in vitro* digestibility of DM and energy (Huang et al., 2017). *In vitro* data obtained from these analyses were compared with *in vivo* data to determine the applicability of using the *in vitro* procedure to predict the feeding values of FW, SMW and FVW.

2.4.1 In vitro enzymatic hydrolysis

In vitro enzymatic hydrolysis was performed to simulate the conditions of apparent ileal digestion of FW, SMW, FVW, and corn. Samples of FW, SMW, FVW, and corn were ground using a mortar and pestle to reduce particle size before subjecting them to *in vitro* enzymatic hydrolysis using pepsin and pancreatin according to the procedure of Boisen and Fernandez (1997). After grinding, 2 grams of each sample (n = 8) were transferred into 500 mL conical flasks with a phosphate buffer solution (100 mL, 0.1M, pH 6.0), and HCl solution (40 mL, 0.2M) was added. The pH of the solution was adjusted to 2.0 using 1 M HCl or 1 M NaOH, and 2 mL of a chloramphenicol (Sigma C-0378, Sheboygan Falls, WI) solution (0.5 g 100 mL/L ethanol) was added to inhibit microbial activity. Fresh porcine pepsin solution (4 mL, 25 g/L, Sigma P-7000, Sheboygan Falls, WI) was subsequently added to the flasks with rubber stoppers and placed in a 39°C water bath for 2 h. After pepsin hydrolysis, 40 ml of phosphate buffer (0.2 M, pH 6.8) and 20 ml of 0.6 M NaOH were added to the flasks, and the pH of the solution was adjusted to 6.8 using 1M HCl or 1M NaOH. Fresh pancreatin solution (2 ml, 100g/L pancreatin, Sigma P-1750 St. Louis, MO) was then added, and the flasks were placed in a 39°C water bath for 4 h. After the hydrolysis period was complete, residues were collected by filtration using a nylon bag (42 μm; Ankom Technologies, Macedon, NY), and washed with ethanol (2 × 25 ml 95% ethanol) and acetone (2 × 25 ml 99.5% acetone). Residues in the bags were then dried in forced-air oven at 60°C for 48 h and subsequently weighed. Hydrolyzed residues from the same treatments (n = 4) were pooled for subsequent *in vitro* fermentation. The remaining 4 replicates were stored individually for GE determination using an isoperibol bomb calorimeter (model 1281; Parr Instrument Co., Moline, IL).

2.4.2 In vitro fermentation

In vitro fermentation was conducted to simulate the *in vivo* fermentation of FW, SMW, FVW, and corn in the hindgut of pigs. The residues of each sample after hydrolysis were used as substrates. Rate of fermentation was monitored using a cumulative gas production technique by Bindelle et al. (2007). Two hundred mg of hydrolyzed residue from each treatment (n = 4) were transferred into 125 mL glass bottles and inoculated with 30 mL buffer solution containing macro- and mirco-minerals (Menke and Steingass, 1988) and fecal inoculum. Feces were obtained from pigs (BW = 120 ± 2 kg) from the Cargill Innovation Campus (Elk River, MN) that were fed a corn, wheat middlings, and soybean meal diet without antibiotics. Feces were collected through rectal stimulation, and samples were placed immediately into an air tight bag that was then stored at 39°C for 1 hour until inoculum preparation was completed using 0.05 g of feces/mL of buffer solution. Fecal inocula were then filtered through a 250 μm screen and transferred into the bottles containing hydrolyzed residues. Fermentation bottles were sealed with rubber stoppers and placed in water bath at 39^{o}C for incubation. An anaerobic environment was maintained throughout the incubation period by adding CO_2 gas. Gas production was measured at 0, 2, 5, 8, 12, 18, 24, 36, 48, and 72 h to monitor the rate of fermentation. The bottles were vented after each measurement, and at the end of 72 h, supernatent from each bottle was collected and frozen before analysis for volatile fatty acids.

2.4.3 Chemical analysis

Gross energy of the hydrolyzed residue was determined using an adiabatic bomb calorimeter (Parr 6400; Parr Instrument Company, Moline, IL) with benzoic acid used as standard. Volatile fatty acid concentrations of the supernatant collected from the fermentation procedure were measured using gas chromatography (Agilent 6890 system, Germany). Two mL of supernatant from each bottle (n = 4) collected from the 72 h fermentation period, were transferred into 10 mL centrifuge tubes and mixed with 2 mL 50% sulfuric acid, 0.4 g sodium chloride, 0.4 mL internal standard, and 2 mL of diethyl ether. The mixtures were then vortexed for 2 min and centrifuged at 3000 × g for 5 min. Finally, the supernatant of the etheric layer was transferred into auto sampler vials before loading into the gas chromatograph mass spectrometer (Agilent 6890 system, Germany) for volatile fatty acid (**VFA**) analysis.

2.4.4 Calculations and Statistical Analysis

In vitro dry matter digestibility (**IVDMD**) was calculated as follows:

IVDMD = (dry weight of sample before hydrolysis or fermentation – dry weight of the residue after hydrolysis or fermentation) / dry weight of the sample before hydrolysis or fermentation

Total tract DM digestibility was calculated as follows:

(100 - IVHDMD) × IVFDMD + IVHDMD

where IVHDM denotes *in vitro* hydrolysis dry matter digestibility and IVFDM denotes *in vitro* fermentation dry matter digestibility expressed as a percentage.

In vitro total tract DE was calculated as the sum of the calculated DE from the hydrolysis procedure and energy released from VFA during fermentation as follows:

In vitro total tract DE = GE of sample before hydrolysis – GE of hydrolysis residue + VFA energy release from fermentation residue

Energy released from VFA (acetic, propionic, butyric, and valeric acids) was assumed to be 0.209, 0.365, 0.522, and 0.678 Mcal/mol, respectively (Weast, 1997). Concentrations of VFAs in the supernatent obtained after the fermentation procedure were multiplied by the assumed energy release values to obtain the total energy release from VFAs. The total tract *in vivo* DE was then calculated as the sum of the energy values obtained from the hydrolysis and VFA production from fermentation. Data were analyzed by the GLM Procedure of SAS, with experiment methods (*in vivo* or *in vitro*) and food waste sources considered as fixed effects. Significance was noted when $P \leq 0.05$ and trends were noted at $0.05 \leq P \leq 0.10$.

2.5 Evaluation of DE and ME prediction equations

The applicability of currently available prediction equations for DE and ME were evaluated to determine whether these equations provide an accurate, fast, and less expensive method to estimate the DE and ME content of FW, SMW and FVW for swine. Energy prediction equations from Noblet and Perez (1993), and stepwise regression equations for DE and ME from Kerr et al. (2017), were evaluated for their accuracy and precision in estimating the DE and ME content of FV, SMW and FVW based on their chemical composition. Gross energy (kcal/kg DM) was estimated according to the chemical composition of the ingredient (Ewan, 1989):

$$GE = 4{,}143 + (56 \times \%\ EE) + (15 \times \%\ CP) - (44 \times \%\ Ash)$$

The concentrations of DE and ME (kcal/kg DM) of food waste sources were calculated using the following equations from Noblet and Perez (1993), where all input variables are expressed as g/kg DM, and GE, DE, and ME are expressed as kcal/kg DM:

$$DE = 1{,}161 + (0.749 \text{ x analyzed GE}) - (4.3 \times Ash) - (4.1 \times NDF) \quad [1]$$

$$DE = 1{,}161 + (0.749 \text{ x calculated GE}) - (4.3 \times Ash) - (4.1 \times NDF) \quad [2]$$

$$DE = 4{,}168 - (9.1 \times Ash) + (1.9 \times CP) + (3.9 \times EE) - (3.6 \times NDF) \quad [3]$$

$$ME = 4{,}194 - (9.2 \times Ash) + (1.0 \times CP) + (4.1 \times EE) - (3.5 \times NDF) \quad [4]$$

$$ME = (1.00 \text{ x } DE\ [1]) - (0.68 \times CP) \quad [5]$$

$$ME = (1.00 \text{ x } DE\ [2]) - (0.68 \times CP) \quad [6]$$

$$ME = (1.00 \text{ x } DE\ [3]) - (0.68 \times CP) \quad [7]$$

Stepwise regression equations for calculating DE (equations 1-4) and ME (equation 9-12) from Kerr et al. (2017) were also used, where all input variables are expressed as % (DM basis), and GE, DE, and ME are expressed as kcal/kg DM as follows:

$$DE = (GE \times 1.26) - 2{,}468 \quad [8]$$

$$DE = (CP \times 56.1) + (EE \times 73.4) + (Ash \times -12.5) - 669 \quad [9]$$

$$DE = (Ash \times -87.5) + 5{,}420 \quad [10]$$

$$DE = (CP \times 46.7) + (EE \times 59.2) + (Ash \times -36.5) + 665 \quad [11]$$

$$ME = (GE \times 1.15) – 2,331 \quad [12]$$

$$ME = (CP \times 48.1) + (EE \times 75.9) + (Ash \times -18.0) – 443 \quad [13]$$

$$ME = (Ash \times -84.0) + 4996 \quad [14]$$

$$ME = (CP \times 36.8) + (EE \times 49.7) + (Ash \times -43.1) + 1,192 \quad [15]$$

Chemical composition of FW, SMW, FVW were used as input variables for the equations, and the calculated values were used to compare with the observed *in vivo* DE and ME content determined in the energy balance experiments (Table 15 and 16).

In addition, equations that included *in vitro* organic matter (**OM**) digestibility and selected chemical composition inputs from Noblet and Jaguelin-Peyraud (2007) were also used to compare predicted DE (MJ/kg DM) vs. *in vivo* determined DE content of food waste sources using the following equations (Table 17):

$$DE = 0.0189 \ OMdv \quad [16]$$

$$DE = 1.12 + 0.0168 \ OMdv + 0.0184 \ EE \quad [17]$$

$$DE = 5.02 + 0.0127 \ OMdv +0.0172 \ EE – 0.0124 \ CF \quad [18]$$

$$DE = 6.05 + 0.0116 \ OMdv + 0.0166 \ EE – 0.0135 \ ADF \quad [19]$$

where all inputs are expressed as g/kg DM, and OMdv denotes *in vitro* digestibility of OM (g/kg DM. Calculated DE values from these equations were converted from MJ/kg DM to kcal/kg DM for comparison purposes by using the conversion factor of 1 MJ = 238.834 kcal (USEIA, 2017).

2.5.1 Statistical analysis

Digestible energy and ME values obtained from the prediction equations were compared to the observed values from the *in vivo* energy balance experiment with a defined range of 95% confidence interval of the observed population. Accuracy was determined by whether the predicted values from the equations fall within the upper and lower boundaries of the calculated margin of error, based on a 95% confidence interval from the values obtained from the *in vivo* energy digestibility experiment.

3. RESULTS AND DISCUSSION

3.1 Chemical composition of food waste

The concentration of GE in FW and SMW was greater than in FVW, which was likely due to the greater concentration of CP and EE in both the FW and SMW compared with FVW (Table 8). The FW contained the greatest concentration of CP because it consisted only of fish carcass remains which contain a substantial amount of protein (Wilson and Cowey, 1985). In fact, the CP content in FW (57.6%) was similar to fish meal (67.5%) reported in NRC (2012). The lipid (EE) content was greatest in SMW because of the relatively high oil content in deli waste and fat trimmings from the meat department of the supermarket. The concentration of minerals was also greater in the FW compared with SMW and FVW. The greater total mineral (ash), Ca, and P content in FW was mainly due to the large proportion of bones and scales in the FW source (Martínez-Valverde et al., 2000), and was comparable to the concentrations in fish meal reported by NRC (2012). Fish waste also had greater concentrations of Lys, Trp, and Met compared with SMW and FVW. However, FW had slightly less Lys, Trp, and Met than the concentrations in fish meal reported in NRC (2012). Thus, the energy and nutrient concentration of the FW source evaluated in this study was similar to that of commercial fish meal currently used in swine nursery diets. The SMW was a mixture of different types of food materials including meat, vegetables, bakery goods, and cooked foods, which resulted in a greater CP content than in FVW, but less than FW. As expected, the FVW source had the least energy, CP, EE, and mineral content because fruits and vegetable are known to contain relatively low amounts of these nutrients and a greater concentration of fiber compared with fish and meat (Greenfield and Southgate, 2003).

3.2 In vivo DE and ME content of food waste sources

The concentration of DE and ME in FW and SMW were greater ($P < 0.01$) than in corn (Table 12), but there were no differences between FW and SMW. In fact, the ME content of FW (4,820 kcal/kg DM) was greater than the NRC (2012) value for fish meal (3,765 kcal/kg DM), and the ME content of FW and SMW (4,922 kcal/kg) was greater than the ME content of full-fat soybeans (4,264 kcal/kg DM) and bakery meal (4,247 kcal/kg DM) reported by NRC (2012). However, although the DE (3,928 kcal/kg DM) and ME (3,875 kcal/kg DM) concentrations in corn were greater ($P < 0.01$) than in FVW (DE = 2,570 kcal/kg DM; ME = 2,460 kcal/kg DM), this source of FVW had greater ME content than soybean hulls (2,139 kcal/kg DM) as reported by NRC (2012). The concentrations of DE and ME in corn obtained in this experiment were similar to those reported in other studies (NRC, 2012; Rojas and Stein, 2013; Oliveira and Stein, 2016). The relatively high DE and ME content in FW and SMW were likely due to the greater concentration of CP and EE in these 2 food waste sources compared with corn and FVW. In contrast, the low concentrations of DE and ME in FVW are likely a result of the greater concentrations of NDF and ADF, which reduce the digestibility of energy in feed ingredients (Noblet and Le Goff, 2001; Wenk, 2001; Le Gall et al., 2009). These results suggest that both FW and SMW can be used as excellent energy sources in swine diets.

The DE to GE ratios for FW (0.79), SMW (0.80), were not different from corn (0.86), but were greater ($P < 0.05$) than FVW (0.62). Corn had the greatest ($P < 0.01$) ME:GE (0.85) compared with FW (0.78), SMW (0.76) and FVW (0.60), which suggests that a greater proportion of the relatively high GE content in FW and SMW is not utilized by pigs compared with that of corn. This is expected because a large proportion of GE in FW and SMW comes from CP, which is less efficiently utilized as an energy source compared with lipids and starch. The DE to GE (0.62) and ME to GE (0.60) ratios of FVW were comparable to wheat bran (DE:GE = 0.60; ME:GE = 0.58) and greater than soybean hulls (DE:GE = 0.48; ME:GE = 0.46) as reported in NRC (2012), which suggests that FVW could be used as a low energy, high fiber ingredient in commercial swine diets, especially for gestating sows. Although SMW had a greater ($P < 0.01$) ME:DE than FW, there were no differences ($P > 0.05$) in ME:DE between SMW and FVW, or FVW and FW. Likewise, the DE:GE and ME:GE for FW and SMW were greater ($P < 0.01$) than FVW. However, the greater ($P < 0.01$) ME:DE in SMW than in FW was related to greater urinary GE loss from nitrogen (NRC, 2012). Excreted urinary energy was about 63.7 kcal/L (data not shown) greater in pigs fed FW group compared with those fed SMW, and the ratio of DE to ME has been shown to be affected by the CP content of the feedstuff (Morgan et al., 1975). High protein intake can lead to greater excretion of urinary nitrogen resulting from increased catabolic activities, and urinary energy content is mainly related to the amount of nitrogen in urine (Morgan et al., 1975; Velayudhan et al., 2015). Increased urinary and fecal N excretion is highly related to excess dietary nitrogen intake, which often results in a lower percentage of N retention especially in diets with an AA imbalance (Noblet and Perez, 1993; Kerr and Easter, 1995). Thus, because the FW contained much greater nitrogen supply than in SMW (62.49% vs. 29.42%, respectively), N excretion in urine from the pigs fed the FW would be expected to be greater than for pigs fed SMW, resulting in the lower DE:ME. This is supported by the results from the amino acid digestibility experiment, where the sum of indigestible essential amino acid content was 2.6 g/kg in FW compared with 2.0 g/kg in SMW.

3.3 In vivo phosphorus digestibility

Phosphorus is the third most expensive component in swine diets and is an essential mineral because its role in many physiological functions, especially bone growth and mineralization (Cromwell, 2005). Total phosphorus content in FW was greater ($P < 0.05$) than in SMW and FVW (Table 13). However, the ATTD of P was greater ($P < 0.05$) in SMW than in FW and FVW. After adjustment for basal endogenous losses, STTD of P of SMW and FVW were greater ($P < 0.05$) than in FW. The total P content in FW was similar to the NRC (2012) value for fish meal (2.95% and 3.13%, respectively), but the P in fish meal (NRC, 2012) appears to be more digestible (STTD = 82%) than FW (STTD = 59%). It is unclear why the P digestibility in FW was much less than the value reported for fish meal in NRC (2012).

Although the total P content in SMW was less than expected, the STTD of P was somewhat greater than expected, which was likely due to a substantial contributions of digestible P from meat, deli, and dairy products. In fact, the STTD of P in SMW (82%) was comparable to STTD of P in meat and bone meal (70%), meat meal (86%), dried skim milk (98%) reported in NRC (2012).

In contrast, it was expected that the total P content in FVW would be relatively low (0.26%), but it was surprising that the STTD of P was very high (74%) because plant derived foods and feed ingredients are known to contain high concentrations of phytic acid, which is an indigestible storage form of P in cereal grains and oil seeds. Phytic acid is poorly utilized by pigs due to the lack of phytase secreted in the gastrointestinal tract, which is the enzyme responsible for releasing phosphate groups from the phytate molecule (Reddy et al., 1982; Cromwell et al., 1995). Therefore, the STTD of P (NRC, 2012) in common feed ingredients such as corn (34%), soybean meal (48%), wheat (56%), sugar beet pulp (63%), and corn dried distillers grains with solubles (65%) is less than observed for FVW in this study. A plausible explanation for the high digestibility of P in FVW is unclear, but may be due to less P is being bound to phytate in fruits and vegetables compared with grains and grain-based ingredients. These results suggest that the FW source evaluated in this study is a concentrated source of P with relatively high digestibility, and although the total P content in SMW and FVW is relatively low, much of the P is digestible in pigs.

3.4 In vivo amino acid digestibility

Thermal processing methods used during the dehydration of food waste may affect the digestibility and bioavailability of AA in food waste, and must be considered when evaluating their use as digestible AA sources in swine diets (Qin et al., 1996; Anandharamakrishnan et al., 2007; Stein and Bohlke, 2007). The AID and SID of AA and CP were not different between FW and SMW (Table 14), but these sources contained greater ($P < 0.05$) AID and SID of all AA and CP than FVW. In fact, negative AID values were observed for most AA in FVW, and after accounting for basal endogenous loses of AA, negative values were still observed for SID of His, Cys, Gly, Pro and Tyr in FVW. Digestibility of AA is reduced by increased concentrations of ADF and NDF in feed ingredients because fiber increases the secretion and reabsorption of endogenous amino acids, which affects the SID of AA (Lenis et al., 1996; Souffrant, 2001; Myrie et al., 2008). The SID of Pro and Gly exceeded 100% for FW, and Gly exceeded 100% for SMW. This may be explained by the potential biosynthesis of these dispensable AA from other amino acids in the enterocytes to produce mucin, which contributes to an increase in endogenous Gly and Pro losses when compared to other AA (Holmes et al., 1974; Reis de Souza et al., 2013). Other studies have reported similar losses of AA when high fiber ingredients were fed to pigs to those observed in this study (Almeida et al., 2011; Reis de Souza et al., 2013; Oliveira and Stein, 2016).

The AID (89.7%) and SID (94.7%) of Lys in FW were greater than published AID (85%) and SID (86%) values for fish meal in NRC (2012). For SMW, the AID of Lys (77.9%) was less than that of soybean meal (86%; NRC, 2012), but the SID of Lys (89.7%) was similar to that of soybean meal (90%; NRC, 2012). The AID and SID of Met (92.4% and 95.0%, respectively) and Trp (91.2% and 99.2%, respectively) in FW were also greater than in fish meal (Met = 86.0% and 87.0%, respectively; Trp = 73 and 76%, respectively) reported by NRC (2012). Both AID and SID of Met and Trp in SMW (Met = 82.9% and 91.0%, respectively; Trp = 83.2% and 96.1%, respectively) were also greater than in soybean meal (Met = 80.0% and 85.0%, respectively; Trp = 87.0% and 89.0%, respectively) in NRC (2012). Considering the high concentration of Lys (4.12%), Met (1.57%), and Trp (0.62%) in FW compared with NRC (2012) values for fish meal, and the high SID of these AA in FW, it is an attractive substitute to traditional fish meal in swine diets.

3.5 Comparison of in vivo and in vitro digestibility of DM and energy

There is increasing interest for using rapid, accurate, low cost alternative *in vitro* methods to evaluate the digestibility of feed ingredients instead of using animals in *in vivo* experiments to determined energy and nutrient digestibility (Święch, 2017). Therefore, the applicability of using a well-established *in vitro* assay to evaluate the energy and DM digestibility 3 sources of food waste was evaluated in this study. *In vitro* digestibility of DM in corn, FW, SMW, and FVW were compared to the *in vivo* DM digestibility data obtained in experiment 1 (Figure 4.). *In vivo* and *in vitro* digestibility of DM did not differ in corn (82.3% vs. 79.4%, respectively) or in SMW (90.1% vs 89.8%, respectively), while differences were observed in FW (84.2% vs 96.0%, respectively; $P < 0.05$) and FVW (63.8% vs. 69.9%, respectively; $P < 0.05$). When comparing the accuracy of using the *in vitro* method to estimate DM and nutrient digestibility, it is important to note that this method estimates the true DM digestibility of a feedstuff compared with *in vivo* determination which includes endogenous losses in the determination of apparent DM digestibility (Reynolds, 2000; Kil et al., 2013). Therefore, our *in vitro* determined DE concentrations of FW and SMW were greater than the *in vivo* DE content (FW = 5,818 vs. 5,057 kcal/kg DM, respectively; SMW = 5,602 vs. 5,071 kcal/kg DM, respectively; $P < 0.05$). The differences in DE values obtained in the two methods may be explained by the endogenous losses of energy that occur using the *in vivo* method, while the *in vitro* method does not account for these endogenous losses (Reynolds, 2000; Kil et al., 2013). In contrast, there were no differences between *in vitro* and *in vivo* determined DE for FVW (2,360 vs 2,570 kcal/kg DM; $P > 0.05$). These results suggest that the use of *in vitro* assays can accurately estimate DM digestibility in SMW, but overestimate DM digestibility in FW and FVW. Furthermore, *in vitro* determination of DE appears to be relatively accurate for FVW, but is overestimated for FW and SMW compared with *in vivo* determined values.

3.5 Applicability of using prediction equations to estimate DE and ME in FW, SMW and FVW

When equations for predicting DE and ME content based on chemical composition of food waste sources were evaluated, the equations from Noblet and Perez (1993) more closely predicted the *in vivo* determined DE of FW, SMW, and FVW than equations from Kerr et al. (2017; Table 15 and 16). Within the Noblet and Perez (1993) equations used for predicting DE values, equation 1 most closely predicted the DE content of FW (observed = 5,057 kcal/kg DM vs. predicted = 5,234 kcal/kg DM), and equation 3 most closely predicted the DE content of SMW (observed = 5,071 kcal/kg DM vs. predicted = 4,909 kcal/kg DM). However, all 3 DE prediction equations from Noblet and Perez (1993) reasonably predicted DE content of FVW (observed = 2,570 kcal/kg DM vs. predicted = 2,731 kcal/kg DM, 2,736 kcal/kg DM, and 2,786 kcal/kg DM for equation 1, 2, and 3, respectively).

In contrast, when prediction equations from Kerr et al. (2017) were used to estimate the ME content of these food waste sources, they more closely estimated the *in vivo* ME values than the equations from Noblet and Perez (1993). Equation 12 from Kerr et al. (2017) most closely predicted the ME content for FW (observed = 4,820 kcal/kg DM vs. predicted = 5,001 kcal/kg DM), SMW (observed = 4,922 kcal/kg DM vs.

predicted = 4,932 kcal/kg DM) and FVW (observed 2,460 kcal/kg DM vs. predicted 2,410 kcal/kg DM). Equation 12 from Kerr et al. (2017) also required use of the fewest input variables among the equations evaluated, and required only GE content to predict ME content in all 3 food waste sources. From these comparisons, it appears that equations from Noblet and Perez (1993) can be used to reasonably predict the DE content, while equations from Kerr et al. (2017) can be used to reasonably predict the ME values of these food waste sources.

We also evaluated the accuracy of using *in vitro* OM digestibility data in equations from derived by Noblet and Jaguelin-Payraud (2007), and results are shown in Table 17. Most of these equations closely predicted the DE content of FW, SMW and FVW relative to the *in vivo* determined values. For instance, equation 17, 18 and 19 from Noblet and Jaguelin-Payraud (2007) reasonably predict the DE content of FW (observed = 5,057 kcal/kg DM vs. predicted = 4,948, 4885, 4852 kcal/kg DM, respectively) and equation 18 reasonably predicted the DE content of SMW (observed = 5,071 kcal/kg DM vs. predicted = 4,978 kcal/kg DM). Lastly, equation 18 and 19 were relatively accurate in predicting the DE content of FVW (observed = 2,570 kcal/kg DM vs. predicted = 2,814 and 2,696 kcal/kg DM, respectively).

These results suggest that using selected published prediction equations, DE and ME content of these 3 food waste sources can be reasonably estimated and be comparable to values obtained from *in vivo* experiments. However, the accuracy of DE and ME prediction equations varies among sources of food waste based on their nutritional characteristics. It appears that using *in vitro* OM digestibility data in the Noblet and

Jaguelin-Payraud (2007) equations resulted in the greatest accuracy of predicted DE for all the sources of food waste.

4. CONCLUSION

In conclusion, results from the current study indicate that both FW and SMW are excellent sources of DE, ME, and digestible amino acids for pigs, and could be used to partially replace corn and soybean meal in swine diets to reduce environmental impact. Specific prediction equations from Noblet and Perez (1993) and Kerr et al. (2017) can be used to provide reasonable estimates of DE or ME content, respectively, of food waste sources. Furthermore, the use of *in vitro* digestibility methods to determine digestible organic matter content of food waste sources, along with DE prediction equations from Noblet and Jaguelin-Payraud (2007) can be used to reasonably estimate the DE content of FW, SMW and FVW of these food waste sources.

Table 8. Analyzed gross energy and nutrient composition of fish waste (FW), supermarket waste (SMW), fruits and vegetable waste (FVW), and corn (as-fed basis)

	Ingredient			
Item	FW	SMW	FVW	Corn
Dry matter, %	92.16	82.89	90.50	85.94
Gross energy, kcal/kg	5,876	5,235	3,731	3,943
Crude protein, %	57.59	24.39	9.17	6.88
Crude fat, %	17.38	29.05	1.29	2.39
Ash, %	15.05	3.47	5.06	1.07
Acid detergent fiber, %	3.40	16.47	20.82	3.09
Neutral detergent fiber, %	3.81	18.50	28.20	7.85
Ca, %	4.83	0.28	0.38	0.01
P, %	2.72	0.31	0.24	0.27
Indispensable AA, %				
Arg	3.62	1.19	0.35	0.28
His	1.32	0.60	0.14	0.19
Ile	2.21	1.14	0.31	0.26
Leu	3.59	1.79	0.44	0.84
Lys	3.79	0.68	0.34	0.23
Met	1.45	0.37	0.10	0.10
Phe	2.06	0.99	0.32	0.35
Thr	2.22	0.92	0.25	0.22
Trp	0.57	0.12	0.04	0.05
Val	2.59	1.19	0.36	0.32
Total	23.41	9.00	2.65	2.85
Dispensable AA, %				
Ala	3.94	1.35	0.40	0.51
Asp	4.86	2.01	0.81	0.46
Cys	0.41	0.27	0.11	0.14
Glu	7.11	3.91	0.99	1.24
Gly	5.74	1.42	0.36	0.27
Pro	3.23	1.34	0.42	0.60
Ser	2.00	0.75	0.25	0.29
Tyr	1.78	0.78	0.17	0.16
Total	29.08	11.82	3.51	3.69

Table 9. Diet composition and analyzed gross energy and chemical content of experimental diets containing fish waste (FW), supermarket waste (SMW), fruit and vegetable waste, and corn used in the energy balance experiment (as-fed basis)

Item	FW	SMW	FVW	Control
Ingredient, %				
Corn	66.90	66.90	66.90	96.90
Food waste source	30.00	30.00	30.00	0.00
Dicalcium phosphate	1.15	1.15	1.15	1.15
Limestone	0.85	0.85	0.85	0.85
Salt	0.40	0.40	0.40	0.40
VTM premix[1]	0.30	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40	0.40
Total	100.00	100.00	100.00	100.00
Analyzed composition				
Dry matter, %	87.73	86.76	87.67	86.53
Gross energy, kcal/kg	4,172	4,108	3,786	3,821
Crude protein, %	15.97	10.12	7.11	5.27
Ether extract, %	12.65	11.10	12.13	2.54
Titanium, %	0.25	0.22	0.23	0.21

[1]The premix provided the following per kilogram of complete diet: vitamin A, 12,000 IU; vitamin D3, 2,500 IU; vitamin E, 30 IU; vitamin K3, 3 mg; vitamin B12, 0.012 mg; riboflavin, 4 mg; niacin, 40 mg; pantothenic acid, 15 mg; choline chloride, 400 mg; folic acid, 0.7 mg; thiamin, 1.5 mg; pyridoxine, 3 mg; biotin, 0.1 mg; Zn, 105 mg; Mn, 22 mg; Fe, 84 mg; Cu, 10 mg; I, 0.50 mg; Se, 0.35 mg.

Table 10. Diet composition and analyzed gross energy and nutrient content of diets used in the phosphorus digestibility experiment (as-fed basis)

Item	FW	SMW	FVW
Ingredient, %			
Corn starch	49.90	49.90	49.90
Food waste	30.00	30.00	30.00
Sucrose	15.00	15.00	15.00
Soybean oil	3.00	3.00	3.00
Limestone	1.00	1.00	1.00
Salt	0.40	0.40	0.40
VTM premix[1]	0.30	0.30	0.30
Titanium dioxide	0.40	0.40	0.40
Total	100.00	100.00	100.00
Analyzed composition			
Dry matter, %	92.78	91.58	92.66
Ca, %	1.55	0.63	0.65
P, %	0.57	0.13	0.08
Ash, %	5.12	2.87	3.09
Neutral detergent fiber %	0.74	0.79	7.16
Acid detergent fiber, %	0.68	0.55	5.47
Titanium, %	0.22	0.23	0.20
Gross energy, kcal/kg	4,366	4,051	4,001

[1]The premix provided the following per kilogram of complete diet: vitamin A, 12,000 IU; vitamin D3, 2,500 IU; vitamin E, 30 IU; vitamin K3, 3 mg; vitamin B12, 0.012 mg; riboflavin, 4 mg; niacin, 40 mg; pantothenic acid, 15 mg; choline chloride, 400 mg; folic acid, 0.7 mg; thiamin, 1.5 mg; pyridoxine, 3 mg; biotin, 0.1 mg; Zn, 105 mg; Mn, 22 mg; Fe, 84 mg; Cu, 10 mg; I, 0.50 mg; Se, 0.35 mg.

Table 11. Diet composition and analyzed gross energy, nutrient, and amino acid (AA) content of diets used in the amino acid digestibility experiment (as-fed basis)

Item	FW	SMW	FVW	N-Free
Ingredient, %				
Corn starch	43.95	43.95	43.95	67.80
Food waste	30.00	30.00	30.00	0.00
Sucrose	20.00	20.00	20.00	20.00
Soybean oil	3.00	3.00	3.00	4.00
Dicalcium phosphate	1.10	1.10	1.10	2.15
Limestone	0.85	0.85	0.85	0.45
Titanium dioxide	0.40	0.40	0.40	0.40
Salt	0.40	0.40	0.40	0.40
VTM premix[1]	0.30	0.30	0.30	0.30
Potassium carbonate	-	-	-	0.40
Magnesium oxide	-	-	-	0.10
Solka-Floc[2]	-	-	-	4.00
Analyzed composition				
Dry matter, %	92.67	92.38	93.16	93.17
Crude protein, %	13.19	6.12	2.84	0.38
Neutral detergent fiber %	1.30	0.79	9.03	1.61
Acid detergent fiber, %	0.19	0.49	5.78	1.35
Gross energy, kcal/kg	3,990	3,991	3,569	3,375
Indispensable AA, %				
Arg	0.80	0.30	0.09	0.01
His	0.31	0.17	0.04	0.00
Ile	0.51	0.27	0.08	0.01
Leu	0.84	0.44	0.15	0.04
Lys	0.93	0.40	0.10	0.02
Met	0.33	0.11	0.03	0.01
Phe	0.48	0.23	0.09	0.02
Thr	0.52	0.22	0.07	0.01
Trp	0.12	0.07	0.03	0.02
Val	0.57	0.29	0.10	0.01
Total	4.58	2.17	0.72	0.13
Dispensable AA, %				
Ala	0.92	0.33	0.12	0.02
Asp	1.12	0.50	0.24	0.02
Cys	0.09	0.06	0.03	0.01

Glu	1.62	0.99	0.33	0.05
Gly	1.35	0.33	0.10	0.02
Pro	0.83	0.34	0.14	0.03
Ser	0.47	0.21	0.08	0.01
Tyr	0.34	0.16	0.04	0.01
Total	6.76	2.93	1.08	0.16

[1]The premix provided the following per kilogram of complete diet: vitamin A, 12,000 IU; vitamin D3, 2,500 IU; vitamin E, 30 IU; vitamin K3, 3 mg; vitamin B12, 0.012 mg; riboflavin, 4 mg; niacin, 40 mg; pantothenic acid, 15 mg; choline chloride, 400 mg; folic acid, 0.7 mg; thiamin, 1.5 mg; pyridoxine, 3 mg; biotin, 0.1 mg; Zn, 105 mg; Mn, 22 mg; Fe, 84 mg; Cu, 10 mg; I, 0.50 mg; Se, 0.35 mg.

[2]International Fiber Corporation., NY, USA.

Table 12. Concentrations of digestible energy (DE), metabolizable (ME) energy, and energy ratios in corn, fish waste (FW), supermarket waste (SMW), and fruits and vegetable waste (FVW) determined in experiment 1 (DM basis)

Item	Corn	FW	SMW	FVW	SEM	*P*-value
DE, kcal/kg	3,928^{b}	5,057^{a}	5,071^{a}	2,570^{c}	98.91	< 0.01
ME, kcal/kg	3,875^{b}	4,820^{a}	4,922^{a}	2,460^{c}	87.96	< 0.01
Energy ratios						
DE:GE[1]	0.86^{a}	0.79^{a}	0.80^{a}	0.62^{b}	0.02	< 0.01
ME:GE	0.85^{a}	0.78^{b}	0.76^{b}	0.60^{c}	0.02	< 0.01
ME:DE	0.98^{a}	0.95^{c}	0.97^{b}	0.96^{bc}	0.004	< 0.01

[a,b,c] Means with different superscripts within a row differ (P < 0.05).
[1]GE = gross energy

Table 13. Concentration, apparent total tract digestibility (ATTD), and standardized total tract digestibility (STTD) of phosphorus in fish waste (FW), supermarket waste (SMW), and fruit and vegetable waste (FVW) determined in experiment 2 (as-fed basis)

Item	FW	SMW	FVW	SEM	*P*-value
Total P, %	2.95	0.38	0.26	-	-
ATTD P, %	56.00^{b}	67.97^{a}	52.95^{b}	2.38	< 0.01
STTD P, %	59.10^{b}	81.94^{a}	74.06^{a}	2.38	< 0.01
Standardized total tract digestible P, %	1.74^{a}	0.31^{b}	0.19^{b}	0.07	< 0.01

^{a,b,c} Means with different superscripts within a row differ ($P < 0.05$)

Values for STTD were calculated by correcting values for ATTD for basal endogenous P loss using 190 mg/kg DM intake (NRC, 2012). The daily basal endogenous P loss was calculated by multiplying daily DM intake by 190 mg/kg DM.

Table 14. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) coefficients of CP and amino acids (AA) in fish waste (FW), supermarket waste (SMW) and fruits and vegetable waste (FVW) determined in experiment 3

	AID					SID				
Item (%)	FW	SMW	FVW	Pooled SEM	P-value	FW	SMW	FVW	Pooled SEM	*P*-value
CP	83.1^{a}	63.5^{a}	-44.5^{b}	8.0	<0.01	95.1^{a}	89.3^{a}	11.4^{b}	7.9	< 0.01
Indispensable AA										
Arg	92.0^{a}	75.3^{a}	-53.1^{b}	13.6	<0.01	99.9^{a}	96.0^{a}	15.0^{b}	13.6	< 0.01
His	89.5^{a}	76.3^{a}	-64.0^{b}	7.3	<0.01	95.2^{a}	87.0^{a}	-15.9^{b}	7.3	< 0.01
Ile	87.1^{a}	78.4^{a}	-34.1^{b}	5.4	<0.01	94.0^{a}	91.3^{a}	8.1^{b}	5.6	< 0.01
Leu	88.2^{a}	80.6^{a}	-14.7^{b}	5.1	<0.01	94.8^{a}	92.7^{a}	21.6^{b}	5.2	< 0.01
Lys	89.7^{a}	77.9^{a}	-35.5^{b}	5.6	<0.01	94.7^{a}	89.7^{a}	9.9^{b}	5.6	< 0.01
Met	92.4^{a}	82.9^{a}	-7.4^{b}	2.7	<0.01	95.0^{a}	91.0^{a}	24.4^{b}	2.7	< 0.01
Phe	87.7^{a}	78.1^{a}	-9.8^{b}	5.4	<0.01	94.4^{a}	92.3^{a}	25.4^{b}	5.4	< 0.01
Thr	83.4^{a}	68.2^{a}	-64.2 ^{b}	9.3	<0.01	93.3^{a}	91.4^{a}	5.2^{b}	9.3	< 0.01
Trp	91.2^{a}	83.2^{a}	15.0^{b}	5.9	<0.01	99.2^{a}	96.1^{a}	49.0^{b}	5.9	< 0.01
Val	83.2^{a}	71.2^{a}	-49.8^{b}	6.8	<0.01	92.8^{a}	89.9^{a}	2.7^{b}	6.8	< 0.01
Dispensable AA										
Ala	88.2^{a}	71.6^{a}	-44.3^{b}	7.2	<0.01	95.1^{a}	90.7^{a}	9.6^{b}	7.2	< 0.01
Asp	83.8^{a}	71.1^{a}	-5.6^{b}	4.0	<0.01	90.8^{a}	86.9^{a}	27.2^{b}	4.0	< 0.01
Cys	65.8^{a}	53.6^{a}	-87.4^{b}	10.1	<0.01	85.9^{a}	82.6^{a}	-20.2^{b}	10.1	< 0.01
Glu	88.3^{a}	81.7^{a}	5.7^{b}	3.7	<0.01	94.3^{a}	91.3^{a}	35.8^{b}	3.7	< 0.01
Gly	89.1^{a}	45.3^{a}	-226. 0^{b}	29.2	<0.01	102.9^{a}	101.2^{a}	-43.0^{b}	29.2	< 0.01
Pro	75.1^{a}	-28.9^{a}	-413.1^{b}	88.2	<0.01	126.7^{a}	96 .4^{a}	-104.1^{b}	88.3	< 0.01
Ser	83.4^{a}	68.4^{a}	-39.8^{b}	7.4	<0.01	92.8^{a}	89.1^{a}	13.3^{b}	7.3	< 0.01
Tyr	86.1^{a}	73.9^{a}	-91.1^{b}	9.6	<0.01	93.7^{a}	90.3^{a}	-21.7^{b}	9.6	< 0.01
Total	86.4^{a}	67.6^{a}	-53.7^{b}	9.6	<0.01	97.1^{a}	91.4^{a}	10.6^{b}	9.6	< 0.01

^{a,b}Means with different superscripts within a row differ (P < 0.05)

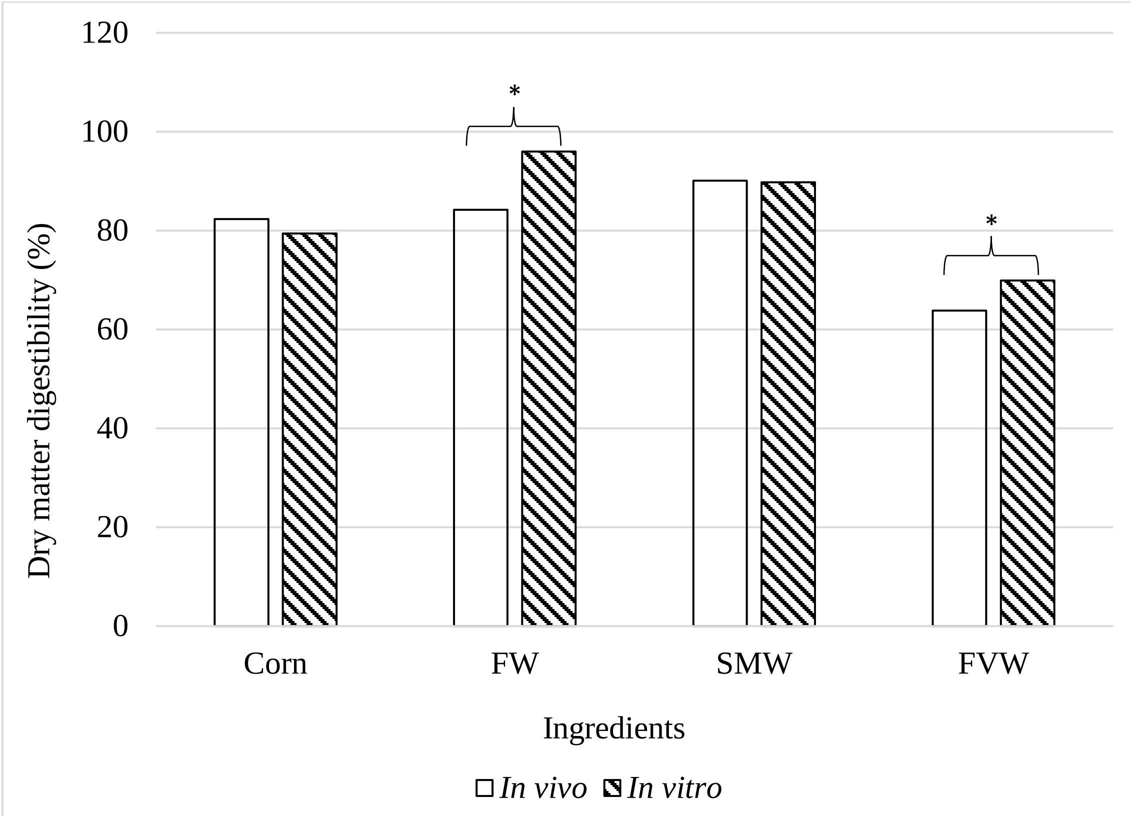

Figure 4. Comparison of in vivo vs. in vitro dry matter digestibility of corn (82.3 vs. 79.4%), fish waste (FW: 84.2 vs. 96.0%), supermarket waste (SMW: 90.1 vs. 89.8%) and fruit and vegetables waste (FVW: 63.8 vs. 69.9%).
***Indicates significant differences between in vitro and in vivo values (P < 0.05).**

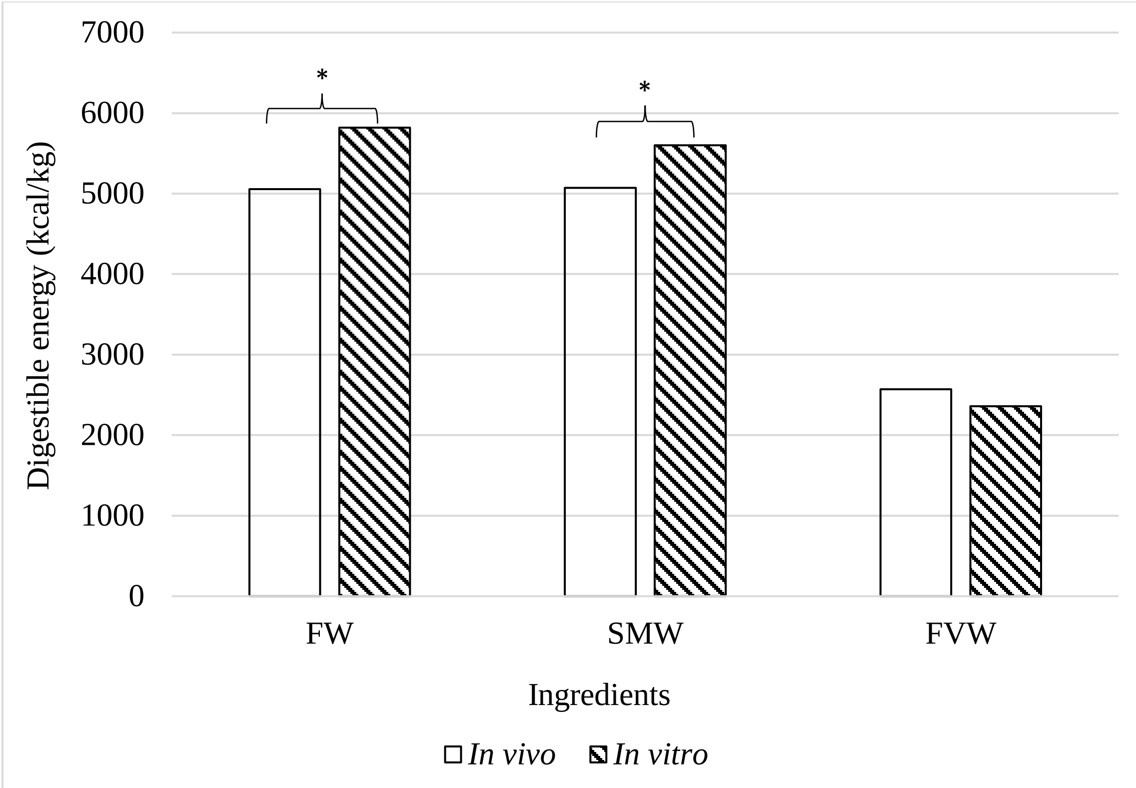

Figure 5. Digestible energy content determined using in vivo or in vitro methods (Noblet and Jaguelin-Peyraud, 2007) in fish waste (FW; 5,057 vs. 5,818 kcal/kg DM), supermarket waste (SMW; 5,071 vs. 5,602 kcal/kg DM), and fruits and vegetable waste (FVW; 2,570 vs. 2,360 kcal/kg DM)
*Indicates significant differences between in vitro and in vivo models (*P* <0.05).

Table 15. Comparison of digestible energy (DE) content determined *in vivo* vs. predicted using equations from Noblet and Perez (1993) and Kerr et al. (2017) in fish waste (FW), supermarket waste (SMW), and fruits and vegetables waste (FVW)

Item	FW	SMW	FVW
Observed mean (*in vivo*)	5,057	5,071	2,570
Margin of error	259	131	251
Upper limit	5,316	5,202	2,822
Lower limit	4,798	4,940	2,319
Noblet and Perez - DE [1]	5,234	4,796	2,731
Noblet and Perez - DE [2]	4,517	4,831	2,736
Noblet and Perez - DE [3]	4,605	4,909	2,786
Kerr et al. - DE [8]	5,566	5,490	2,727
Kerr et al. - DE [9]	4,017	3,502	-66
Kerr et al. - DE [10]	3,991	5,053	4,931
Kerr et al. - DE [11]	4,104	3,961	1,019

Table 16. Comparison of metabolizable energy (ME) content determined *in vivo* vs. predicted using equations from Noblet and Perez (1993) and Kerr et al. (2017) in fish waste (FW), supermarket waste (SMW), and fruits and vegetables waste (FVW)

Item	FW	SMW	FVW
Observed mean (*in vivo*)	4,820	4,922	2,460
Margin of error	231	101	229
Upper limit	5,051	5,023	2,689
Lower limit	4,589	4,821	2,232
Noblet and Perez - ME [4]	4,090	4,759	2,749
Noblet and Perez - ME [5]	4,092	4,631	2,667
Noblet and Perez - ME [6]	4,810	4,596	2,662
Noblet and Perez - ME [7]	4,477	4,671	2,776
Kerr et al. - ME [12]	5,001	4,932	2,410
Kerr et al. - ME [13]	3,700	3,557	52
Kerr et al. - ME [14]	3,624	4,644	4,526
Kerr et al. - ME [15]	3,725	3,836	1,395

Table 17. Prediction of digestible energy (DE) content in fish waste (FW), supermarket waste (SMW), and fruits and vegetables waste (FVW) using a combination of *in vitro* organic matter digestibility and nutrient content using equations from Noblet and Jaguelin-Peyraud (2007)

Item	FW	SMW	FVW
Observed value (*in vivo*)	5,057	5,071	2,570
Margin of error	259	131	251
Upper limit	5,316	5,202	2,822
Lower limit	4,798	4,940	2,319
Noblet and Jaguelin-Peyraud - DE [16]	4,333	4,052	3,155
Noblet and Jaguelin-Peyraud - DE [17]	4,948	5,410	3,135
Noblet and Jaguelin-Peyraud - DE [18]	4,885	4,978	2,814
Noblet and Jaguelin-Peyraud - DE [19]	4,852	4,750	2,696

Chapter 4: Environmental impact of utilizing food waste sources as feed ingredients in swine production

Summary

Results described in previous chapters have demonstrated that the nutritional value of various sources of food waste vary substantially and consequently the utilization in swine diets but it is unknown if the sources with greatest nutritional value would provide the best environmental saving. Therefore, the objective of this study was to use the most updated composition of food waste to investigate the potential environmental impacts of using various sources of food waste in commercial swine diets when they replace corn and soybean meal. For this purpose, non-renewable energy (NRE), non-renewable resource use (NRRU), acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) of utilizing food waste in swine diets was estimated by calculating the replacement potential of corn and soybean meal with the food waste ingredients. The nutritional composition were obtained from chemical composition of supermarket (SM), university residence hall (RH), transfer station (TS), and source separated organics (SSO). Likewise, data from a second project were obtained from pigs fed fish waste (FW), supermarket waste (SMW), and fruits-vegetable waste (FVW). These sources of food waste were selected to represent various levels in the food waste generation chain from pre-consumer waste, post-consumer waste, and thermally treated waste. The environmental impact of animal feed ingredients and the subsequent replacement with food waste sources in complete diets was calculated using the environmental factors for corn and soybean meal. Descriptive statistics were used to

compare environmental impact parameters among sources of food waste. Results showed that using supermarket waste (wet or dried) had the greatest potential to displace corn and soybean meal in commercial swine diets due to the energy and amino acid content. Thus, there was a reduction of NRE (693.12 and 665.39 Mcal metric ton of feed produced) and GWP (287.9 and 271.7 kg CO_2 eq./metric tonne of feed produced). The RH waste can also contribute to meaningful reduction in NRE (665.39 Mcal/metric ton of feed produced) and GWP (274.5 kg CO_2 eq./metric ton of feed). The sources of food waste with greatest concentration of nutrients provided the greatest opportunity for displacement of corn and soybean meal and consequently the greatest calculated environmental savings. However, it is also important to recognize the current lack of information in the environmental cost of producing feed ingredients with these food waste streams such as initial production cost of these materials and their processing, which might offset the benefits it provides environmentally. Nonetheless, the results suggested that food waste can potentially be a highly desirable feed ingredient alternative when considering the potential environmental impact of pork production while it is also critical to evaluate the environmental cost of production when utilizing these materials in order to fully understand the cost and benefits balance.

1. Introduction

In 2014, pork production was the biggest contributor to global meat production accounting for 36.3% percent, and global meat consumption is predicted to continue to grow at a high rate (1.5% per year 1930 to 2027) as global meat demand intensifies

(FAO, 2014). With this rapid growth in global pork production to meet the increasing global meat demand, improved efforts are needed to avoid worsening negative environmental impacts of the industry, such as greenhouse gas (**GHG**) emissions and the excessive wastage of natural resources (Macleod et al., 2013). The world livestock production sector has been determined to be responsible for 9% of the world's emission of GHG (EPA, 2017). Sustainability of agricultural food production systems should not only be focused on increasing the supply of food, but approaches to reduce the negative environmental impacts of food production should also be considered. According to Thoma et al. (2011), feed and manure are the primary contributors to greenhouse gas (GHG) emissions in the life cycle of animal production. Feed accounts for about 40% of the total GHG emissions during the production of pork while manure contributes another 35% (Thoma et al., 2011). Moreover, production of feed ingredients and land manure runoff also contribute to the eutrophication (**EP**) and acidification potential (**AP**) of pork production averaging 33 to 53% EP for feed, 40 to 45% EP for manure and 23 to 53% AP for feed, 45 to 51% AP for manure (Kebreab et al., 2016). Throughout the entire pork supply chain (on-farm production to consumption), the nursery to finishing phase accounts for the most GHG emissions, representing 52.5% of the total emissions (Thoma et al., 2011). The GHG emissions burden from feed is derived mainly from input of fertilizers and energy used to produce crops that are commonly used as feed ingredients including corn, soybean, and corn distillers dried grains with solubles (DDGS). Thus, the use of feed ingredients plays an important role in the environmental impact of pork production, and the use of alternatives can provide opportunities for improving the environmental impact of pork production (Kebreab et al., 2016).

In the U.S., the annual production of feed for pigs is about 150 million tons, while more than 38 million tons of food waste was generated in the United States in 2014, and only 5 percent of it was diverted from landfilling and incineration (USEPA, 2017). Disposing of food waste in landfills also contributes significantly to negative environmental impacts such as GHG emissions and wasted natural resources. When food reaches the landfill, it emits significant amounts of methane, which is considered a primary contributor to global warming and has more than 25 times greater effect than carbon dioxide (IPC, 2014). By using United States Environmental Protection Agency's Waste Reduction Model (WARM) model, the total GHG emission of food waste from initial transportation to landfilling has been estimated to be 635 $kgCO_2$ eq/ metric ton (Schmitt et al., 2018). The Food and Agriculture Organization (FAO) estimates that global food waste GHG emissions are greater than total GHG emissions from every country in the world except the U.S. and China (FAO, 2013). Furthermore, food waste contributes to 12-15% of global water consumption, which is an essential environmental resource that must be conserved (Kummu et al., 2012). Due to the increased realization of the environmental costs of food waste, there has been an increasing interest in utilizing food waste as animal feed. The U.S. Environmental Protection Agency (USEPA) has recommended that diverting food waste to animal feed be considered as the third priority below "source reduction" and "feeding hungry people" within the Food Recovery Hierarchy (USEPA, 2017). Thus, if food waste is recycled into swine feed, there would be environmental benefits by preventing landfill methane emissions, reducing energy and resources for crop production to produce animal feed, and would reduce the environmental burden of the nursery to finishing phase of pork production systems which is a primary contributor to GHG emissions.

2. Materials and Methods

2.1 Environmental impact of replacing corn and soybean meal with food waste from different stages of the food supply chain

Nutrient profiles of 4 different sources of food waste samples (n = 121) that were generated at two different levels: pre-consumers (supermarket **SM)** and post-consumers (University residence hall **RH,** household source separated organics **SSO,** and municipal organic waste collected at a transfer station **TS**) were obtained from previous studies, and data were used as inputs for all calculations (Table 18). Nutrient values of corn and soybean meal from NRC (2012) were also used as inputs for diet formulation. The environmental impact of replacing corn and soybean meal in swine diets (during the growing-finishing phase) with these waste materials was calculated using a two-step procedure. First, a linear least cost diet formulation software program (National Swine Nutrition Guide Diet Formulation and Evaluation Software) was used to formulate a typical corn-soybean meal diet (**CON**) to meet the metabolizable energy (**ME**) and digestible nutrient requirements (NRC, 2012) for growing finishing pigs with body weight of 25 to 50 kg. Next, an Excel program with least cost-optimization macros was used to formulate diets containing similar energy and digestible nutrient content using the food waste ingredients (with a price set to the lowest cost of 1 dollar per ton). Food waste sources were used to replace corn and soybean meal in the CON diet to meet the requirements (NRC, 2012) for growing pigs with the same body weight (25 to 50 kg) as used in formulating CON. Thus, the excel program would prioritize the use of the food waste ingredients within the diets due to the set low cost while achieving the appropriate nutritional content of the overall diet to meet the ME and digestible nutrient requirements. As a result, this method produced a total of 121 different complete diets containing different diet inclusion rates of the 4 food waste sources at maximum possible inclusion to meet NRC nutrient requirements. The 121 diets were formulated to determine the amount of displacement of corn and soybean meal using the food waste ingredients, compared with the control diet which contained 0% of food waste (a typical corn and soybean meal diet). After obtaining the difference in the amount of corn and soybean meal displaced between the CON diet and the 121 diets containing food waste sources, the environmental impacts were calculated based on reference environmental impact values of using corn and soybean in feed production from Mackenzie et al. (2016). These estimates were obtained from previous life cycle inventory studies on Canadian crop production (Mackenzie et al., 2016; Pelletier et al., 2008). These factors represent the partial life cycle of using these ingredients in pork production as feed identified as cradle to swine farm gate impacts (which omitted the use and disposal phase of the ingredients) with a function unit of 1 kg expected carcass weight of pork delivered from farm gate (omitting the transport of live pigs and slaughtering). Five factors were considered in the calculation, which included non-renewable energy use (**NRE**), non-renewable resource use (**NRRU**), acidification potential (**AP**), eutrophication potential (**EU**), and global warming potential (**GWP**). While the impact factors from Mackenzie et al. (2016) are for Eastern Canada, they were considered to be similar to pork production systems in the United States. By multiplying the each of these 5 environmental factors with the relative usage of corn and soybean meal in the CON diet and their reduced amounts in the 121 diets containing each food waste source, the environmental impacts of replacing corn and soybean meal with food waste ingredients per metric ton of feed produced were obtained.

2.2 Environmental impact of replacing corn and soybean meal with food waste from pre-consumer sources

Nutritional profiles of 3 different dehydrated pre-consumer food waste (fish waste, **FW**; supermarket waste, **SMW**; fruits and vegetables waste **FVW**) from a previous study were used as inputs in all environmental impact calculations. The same method to formulate diets previously described, was used to formulate 4 diets including a corn-soybean control diet and three diets containing each of the three food waste sources (SMW, FW and FVW). Subsequently, differences in the amount of corn and soybean used between the reference diet and the food waste diets were calculated in Excel on a kg per metric ton basis. The environmental impact of replacing corn and soybean meal with each food waste source was then calculated based on the reference environmental impact values from Mackenzie et al. (2016) as previously described.

2.4 Greenhouse Gas Equivalencies Perspective

In order to put into perspective the impact of replacing corn and soybean meal in swine diets with the food waste sources on environmental savings, the U.S. Environmental Protection Agency Greenhouse Gas Equivalencies Calculator was used to calculate the impact equivalence of using food waste as swine feed to the carbon dioxide release of passenger vehicles.

2.3 Statistical analysis

Environmental impact data were analyzed using the GLM procedure of SAS 9.3 (SAS Inst. Inc., Cary, NC). Individual food waste sources were considered the main effect. Significant differences were determined if $P \leq 0.05$ and trend are considered when $P < 0.01$. For the comparison of differences in environmental impact of replacing corn and soybean meal with dehydrated pre-consumer food waste, only numerical comparisons could be made due to the limited amount of data.

3. Results

3.1 Environmental impact of replacing corn and soybean meal with food waste from different stages of the food supply chain

Five environmental impact values were evaluated based on the substitution rates of corn and soybean meal by four food waste sources (SM, RH, TS; and SSO; Table 18). For non-renewable energy use (**NRE**), SM waste had the highest ($P \leq 0.05$) potential of usage reduction with compared with RH, TS, and SSO. For non-renewable resources used (**NRRU**), SM waste also posts the highest ($P \leq 0.05$) potential in reduction compared with RH, TS, and SSO. Furthermore, SM waste also posts the highest potential in reducing acidification potential, eutrophication potential and global warming potential when compared with the other 3 food waste sources ($P \leq 0.05$).

3.2 Environmental impact of replacing corn and soybean meal with food waste from pre-consumer sources

For food waste from dehydrated pre-consumer sources, the greatest environmental impact saving was observed in supermarket waste (**SMW**), this source of food waste can potentially save 656.79 Mcal of NRE, 1.18 kg Sb eq of NRRU; reduce 3.85 kg SO_2 eq of AP, 0.83 kg PO_4 eq of EP and 271.1 kg CO_2 eq of GWP per metric ton of SMW used. The environmental impact of the SMW substitution is significantly greater when compared to the potential environmental impact of FVW substitution for all parameters tested (NRE, NRRU, AP, EP, or GWP). On the contrary, FW had the least impact in NRE and only modest savings in NRRU, AP, EP, and GWP when compared to those values obtained from SMW substitution.

4. Discussion

The production of crops for animal consumption requires inputs of energy and natural resources such as water and land. In addition, feeding diets to animals also produces greenhouse gases (e.g. methane, carbon dioxide) attributable to the production of manure and demand of energy input from burning fossil fuels (Koneswaran et al., 2008; Mackenzie et al., 2016). Consequently, the food animal production sector can contribute to decrease global environmental impact of food production. The highly environmental intensive diets (considering the input of energy and use of natural resources) make swine feed the second largest hotspot for life cycle GHG emissions, and ranks swine production as the second greatest contributor after beef production in terms of their overall environmental impact (Costello et al. 2015; Thoma et al. 2011). In swine production systems, feed production contributes 50-85% of its overall climate change impact, 64-97% of eutrophication potential, 70-96% of energy used and 100% of land use

(Wilfart et al., 2016). In the United States, corn and soybean meal are the most commonly used ingredients for swine diets (Boggess et al., 2008). Thus, the goal of replacing these frequently used ingredients with food waste can greatly alleviate the environmental impact of U.S. pork production because a high proportion (95%) is disposed in landfills and significantly contributes 635 kg CO_2 eq/metric ton to GHG emissions (Dorward, 2012).

Our results suggest that when considering the differences between the food waste generated at different stages within the food supply chain, the SM waste had the greatest potential of producing the greatest environmental savings of pork production when used in swine diets. This is due its potential of large proportion substitution of food waste into swine diets to replace corn and soybean meal because of its abundance of energy and amino acids. Source of food waste that were mixed with significant amount of low value components such as food waste from the transfer station and source separated organic waste had comparatively lower potential for reducing negative environmental impacts because of their lower energy and digestible amino acid content.

The greatest environmental savings was obtained when diets were formulated with SMW, to put this into perspective, it is estimated that a typical passenger vehicle produces 8.8 kg of CO_2 per gallon of fuel (EPA, 2014). Thus, implementing SMW into swine feeding programs can potentially reduce CO_2 emissions equivalent to 32.7 gallons of CO_2 generated from cars in each ton of feed produced. Similarly, for food waste generated from pre-consumer level and dehydrated through heat treatment, it was also observed that SMW can potentially reduce the most non-renewable energy use and global warming potential compared with the other 2 sources. Using the U.S. EPA greenhouse gas equivalence calculator, if all the pigs in the state of Minnesota (~ 8.3 million head) were fed diets containing SMW waste, the Minnesota pork industry could potentially reduce the CO_2 emissions equivalent to 178,210 passenger vehicles driven for a year (assuming an average of 818 pounds of feed consumed from farrow to finish for 1 pig; Lammers et al., 2007).

The differences between the environmental impact reductions from using food waste as feed ingredients in swine diets, were dependent on the amount of corn and soybean meal that was replaced in the diet formulations. In this case, the SMW replaced the greatest amount of corn and soybean meal in the diet formulations, while FW inclusion in the diets was limited by its high calcium concentration. The phosphorus to calcium ratio is important to the growth of pigs and the ratios are normally kept between 1 to 1.25 (Cromwell et al., 1969; Qian et al., 1996). Therefore, the high amount of calcium in the FW mixture limited its inclusion rate and hence, limited the potential to replace corn and soybean meal. Thus, a negative value was obtained in the NRE calculation because more corn was needed in the diet in order to compensate for the limited inclusion rate of FW. On the other hand, it is important to note that the true value of FW might not have been completely captured in the current method utilized in the calculation since another important usage of the fish waste was not accounted for in the factors. For instance, fish waste, instead of substituting major ingredients such as corn and soybean meal, it can potentially be a useful alternative for fish meal in swine diets. Fish meal is a feed ingredient produced by the fishing industry, and has been often used in starter pigs diets to provide highly digestible amino acids to support the growth of starter pigs (Stoner et al., 1989). On average, about 25% of global fish catches have been used for fish meal and fish oil production over the past 6 decades (Cashion et al., 2017). This vast conversion of fish proteins from wild fisheries to fish meal for use in animal feeds hinders our ability to achieve global food security since many of the fishes used to produce fish meal are food grade which can be used for direct human consumption (Cashion et al., 2017). Thus, with similar energy and digestible amino acid content of FW compared with fish meal, it can be used in starter pig diets to reduce fish meal demand and reduce the pressure on global fisheries and increase the sustainability of the global fishery system (Oslen and Hasan, 2012). Thus, FW can provide alternatives to fish meal and relief the pressure of the over-harvesting of wild fish.

Due to the low inclusion rate of FVW in the formulation due to its low concentration of energy and digestible amino acids, the environmental impact of utilizing FVW in swine diets are not as significant as SMW. However, although using FVW in swine diets has significant limitations, it could be combined with FW or SMW to balance energy and digestible nutrient composition of diets for pigs while benefiting from reducing environmental impacts. However, further research is required to determine the possibilities of combining different sources of food waste.

It is important to note that the calculation performed in the current study did not take into account the environmental impact of processes needed for the food waste to be incorporated into the swine diets. These impacts would account for processes such as initial production of these food materials when intended for human use, transportation, processing (e.g. drying) and removal of packaging before they can be used as animal feed. These processes require input of energy and hence lead to the production of GHG and use of resources such as land. Thus, these impacts might offset the calculated benefits provided above if they were accounted for in the system. Furthermore, the environmental reference values used for calculations were obtained from a study based on Canadian crop production, which the global warming potential (GWP) associated with crop production can be spatially different when compared to the U.S. Also, the energy generation mix in the United States is different than Canada which can also affect the results.

Besides the limitations of the current method mentioned above, if we were to further investigate into the true environmental benefits of incorporating food waste into animal feed at a large scale, there are few crucial steps needed before a more comprehensive Life Cycle Assessment (LCA) can be established. First, it is important to consider the production cycle of food waste when used as animal feed from the transportation of materials to final feed preparation. The process of transporting and dehydrating these food waste materials also contributes to the environmental value of these potential feed ingredients just like other traditional ingredients that requires the input of energy and natural resources to grow and harvest. These environmental costs will then be taken into account when allocating the environmental impact value of the food waste sources during the inventory analysis of the LCA (Eriksson e al.,2005; Monteiro and Dourmad, 2018; Kebreab et al., 2016). Secondly, it is also important to understand the value of these food waste in animal diets in terms of production (growth and health of animals). This can be done by performing digestibility and animal growth studies with the target food waste to determine the correct inclusion amount in animal diets. After the studies are completed, the appropriate proportion of food waste usable in swine diet can be clearly established and hence, used for food waste to animal feed conversion quantity estimation within the swine production system in the LCA before calculating the overall impact. Hence, in order to fully understand the actual environmental benefits of utilizing food waste as a feed ingredient in production systems, it is important to gather information about a standardized procedure to process food waste specified for the source and its value to a production system in terms of realistic growth efficiency. This information will be crucial when establishing a more comprehensive LCA since they allow researchers to allocate a “cost” and realistic rate of utilization of food waste in production systems.

5. Conclusion

The results of this study have demonstrated a concept of the potential displacement of environmentally costly ingredients (corn and soybean meal) with food waste, which can reduce the environmental footprint of pork production while also diverting food waste from landfills to prevent further GHG emission. However, calculations were based on assumptions that needs to be further verified by conducting studies that demonstrate the true applicability of food waste as feed ingredients in production animals and the complete life cycle assessment of food waste being utilized as feed ingredients. Further researches should investigate the environmental cost of producing feed ingredients with food waste streams in order to establish a knowledge of how these processes involved in feed production from food waste would affect the environment negatively and how it balances with the benefits discussed in the section.

Thus, further research is needed to consolidate the idea of diverting food waste into animal feeds targeting its real-world applicability.

Table 18. Calculated environmental benefits of using food waste from supermarket (SM), university residence hall (RH), transfer station (TS), or source separated organics (SSO) when replacing corn and soybean meal in diets for growing pigs

Source*	SM		RH		TS		SSO		
Item	Mean	SD	Mean	SD	Mean	SD	Mean	SD	SEM
NRE[1]	693.12[a]	38.05	665.39[b]	29.52	639.58[c]	37.29	642.21[c]	17.45	7.17
NRRU[2]	1.25[a]	0.07	1.19[b]	0.05	1.14[c]	0.07	1.15[c]	0.03	0.01
AP[3]	4.26[a]	0.50	3.89[b]	0.39	3.55[c]	0.49	3.58[c]	0.23	0.09
EP[4]	0.92[a]	0.11	0.84[b]	0.08	0.77[c]	0.10	0.78[c]	0.05	0.02
GWP[5]	287.9[a]	18.37	274.5[b]	14.25	262.0[c]	18.00	263.3[c]	8.41	3.47

[1] Nonrenewable energy use, Mcal per t of complete diet.
[2] Nonrenewable resource use, kg antimony (Sb) equivalents per t of complete diet.
[3] Acidification potential, kg SO_2 equivalent.
[4] Eutrophication potential, kg PO_4 equivalent.
[5] Global warming potential, kg CO_2 equivalent.
* Food waste sources including Supermarket waste, University residence hall waste, transfer station waste and source separated organic waste mentioned in Chapter 2 of the thesis

Table 19. Calculated environmental impact per metric ton of feed produced by substituting corn and soybean meal with dehydrated pre-consumer food waste including fish waste (FW), supermarket waste (SMW) and fruits and vegetable waste (FVW) in diets for growing pigs

Sources*	**FW**	**SMW**	**FVW**
Impact saving, /t			
NRE[1] (Mcal)	-6.17	656.79	24.72
NRRU[2] (kg Sb eq)	0.01	1.18	0.04
AP[3] (kg SO_2 eq)	0.30	3.85	0.13
EP[4] (kg PO_4 eq)	0.06	0.83	0.03
GWP[5] (kg CO_2 eq)	0.62	271.1	10.02

[1] Nonrenewable energy use, Mcal per t of complete diet.
[2] Nonrenewable resource use, kg antimony (Sb) equivalents per t of complete diet.
[3] Acidification potential, kg SO_2 equivalent.
[4] Eutrophication potential, kg PO_4 equivalent.
[5] Global warming potential, kg CO_2 equivalent.
* Food waste sources including Supermarket waste, University residence hall waste, transfer station waste and source separated organic waste mentioned in Chapter 2 of the thesis

Overall Summary

The objective of this thesis was to explore the potential of using various sources of food waste as swine feed. This encompassed the evaluation of suitable food waste stream within the food supply chain, the feeding value of food waste from a suitable waste stream and the potential environmental benefits when these food wastes are incorporated into the animal production system. By combining the information presented in this thesis, it creates a basic knowledge of how food waste can be used effectively as animal feed.

Results from Chapter 2 suggested that food waste that are generated upstream in the food supply chain (supermarket and leftover from residence dinning hall) have greater feeding value due to the minimal dilution of non-food organics that might affect the quality of the material when used as animal feed. High concentration of energy and amino acids have been observed in these upper stream food waste such as supermarket waste which contained significantly greater GE, NE and amino acids (Lys, Met, Thr and Trp) than the other food waste sources (transfer station, source separated organics). Thus, these findings suggested that supermarket waste might be the most suitable food waste source amongst the food waste generated along the food supply chain as a result of the level of separation and nutritional value of the waste source.

Results from Chapter 3 demonstrated that specific food wastes from the upper supply chain (Fish Waste and Supermarket Waste) have greater potential as a feed ingredient in production animal feed due to their exceptional content in DE, ME and digestible AA obtained experimentally *in-vivo*. It was shown that fish waste and supermarket waste have greater feeding value in terms of DE, ME and digestible amino acids when compared to fruit and vegetable wastes. Moreover, currently available equations can reasonably predict the DE and ME content of the food waste sources while the utilization of *in-vitro* digestibility methods can also provide reasonable estimations. Taken together these two tools can help food waste reduction practitioners to estimate the nutritional and commercial value of food waste relatively rapidly and at low cost. However, additional research is needed to improve the accuracy of these prediction equation specifically when applied to ingredients as variable as food waste. A more restrictive selection of waste stream to be used can also help improve the prediction accuracy of energy and digestible amino acids when these food wastes are used as feed ingredients.

Chapter 4 explored the potential environmental benefits of utilizing food waste as animal feed. The results suggested that regardless of origins, food waste that contain the greatest nutritional value might be the most environmentally impactful ingredients due to their potentiality of replacing large quantity of traditional ingredients in production animal diets such as corn and soybean meal. Results showed that the supermarket waste appeared to be the most beneficial ingredients since it replaces the most corn and soybean meal in the test diets, which in turn reduces the environmental footprint of the diets most significantly. However, it is important to note that in order to fully understand the environmental advantages of replacing corn and soybean meal in swine diets with suitable sources of food waste, more specific researches are needed to further justify the results such as the investigation of the environmental food print of processing food waste into animal feeds and the true feeding value of a selected food waste when used commercially at a large scale. When these results are accounted for, a more realistic estimation of the environmental benefits of food waste to animal feed diversion shall be established.

In spite of the limited information provided and the need of further experimentally justified results, our research provided an insight to the possibilities of intensifying the usage of food waste as animal feed. These results can provide ground for further researches into the applicability of food waste being used as animal feed. The thesis provided confidence in the future steps necessary for fully utilizing food waste as animal feed.

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